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UNIVERSITY OF ALBERTA

A BASIN STUDY OF THE SOUTHERN ATHABASCA OIL SANDS DEPOSIT

BY

© MICHAEL JOSEPH RANGER

A THESIS SUBMITTED TO THE FACULTY OF
GRADUATE STUDIES AND RESEARCH IN PARTIAL
FULFILMENT OF THE REQUIREMENTS FOR THE
DEGREE OF DOCTOR OF PHILOSOPHY

DEPARTMENT OF GEOLOGY

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Dr. S. George Pemberton

To Mary and Norman.

ABSTRACT

A sequence stratigraphic framework is proposed for the McMurray Formation of south Athabasca. Detailed log correlations from over 1700 wells demonstrate that there exist stacked, prograding, shoreface parasequence sets that can be regionally correlated over the southern Athabasca Oil Sands Deposit. These parasequence sets represent the highstand systems tract. They are best preserved in the south, and are also preferentially preserved towards the top of the McMurray Formation. However, the dominant depositional elements in the basin are lowstand channels incised into the parasequence sets. These channels are filled with a complex estuarine facies succession consisting dominantly of sandy to muddy estuarine point bars. The basal fill of some of the deeper channel valleys consists of freshwater fluvial point bars.

Statistical facies analysis, using clustering techniques and Markov analysis, differentiates a large database of facies descriptions into three major successions that correspond closely with the proposed stratigraphic framework for the McMurray Formation. These successions are interpreted as: 1) a simple coarsening-upward shoreface succession 2) a complex of interrelated channel fill deposits and 3) rooted paleosols. The top of the McMurray Formation appears to be an erosion surface, and may be a sequence boundary.

Wabiskaw sands overlying the McMurray Formation in the Wabasca area are reinterpreted as a lowstand shoreface preserved on a shallow shelf. They can be shown to onlap the shoreline of a Paleozoic highland, which remained exposed to the northwest during early Clearwater transgressions.

The bitumen/water contact in the southern Athabasca deposit is immobile, and dips to the southwest at an angle only slightly less than the reservoir host strata. This dip is caused by subsidence of the foreland trough during the Laramide orogen and indicates that the generated oil had migrated, become trapped, and degraded to immobile bitumen very early at the onset of the Laramide orogen, probably no later than Late Cretaceous. The structure of the reservoir can be restored to its approximate configuration at the time of trapping and oil degradation by mapping the top of the reservoir using the bitumen/water contact as a datum. The trap is shown to be a shallow anticlinal structure of immense size. There was probably a stratigraphic component to the trap to the northeast, where overlying Clearwater shales onlapped the Precambrian regolith.

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CHAPTER I

INTRODUCTION

The vast bitumen reserves of the Athabasca Oil Sands Deposit (Fig. I-1) presently account for about 14% of Alberta's liquid hydrocarbon production (Webber, 1989). The importance of understanding the McMurray Formation of northeastern Alberta cannot be overstated, since it is the main Athabasca reservoir, and hosts one of the largest hydrocarbon accumulations in the world. Unfortunately, the reality faced by every researcher who undertakes a study of the McMurray Formation is that these Lower Cretaceous sediments appear to be one of the most complex depositional systems in the Western Canada Basin. Most of the data available is from the subsurface, although a few excellent outcrop exposures exist in the northeastern part of the deposit. However, even with good quality cores and geophysical logs from closely spaced wells, which in some cases may be only a few hundred metres apart, lithostratigraphic units within the McMurray Formation are difficult and often impossible to correlate for any distance (Carrigy, 1971; Mossop, 1980; Flach, 1984).

Seminal work on the outcrop exposures around Fort McMurray has contributed greatly to a basic understanding of the sedimentology of the reservoir (Mossop, 1980; Mossop and Flach, 1983; Flach, 1984; Flach and Mossop, 1985). Flach and Mossop have demonstrated that the best reservoirs of the Athabasca Deposit are deep, sand-filled, incised channels. This observation is of prime economic importance. However, these channels, or at least their sandy facies, appear to be of relatively limited extent and, while common in outcrop, there has been little success in extrapolating the outcrop observations into the subsurface (Mossop, 1980). It appears that sandy facies of the McMurray Formation are preferentially preserved in outcrop, therefore giving a biased, but highly visible and influential sample of the reservoir architecture.

The main objective of this thesis was to resolve the stratigraphy and sedimentology of the subsurface McMurray Formation on a regional scale.

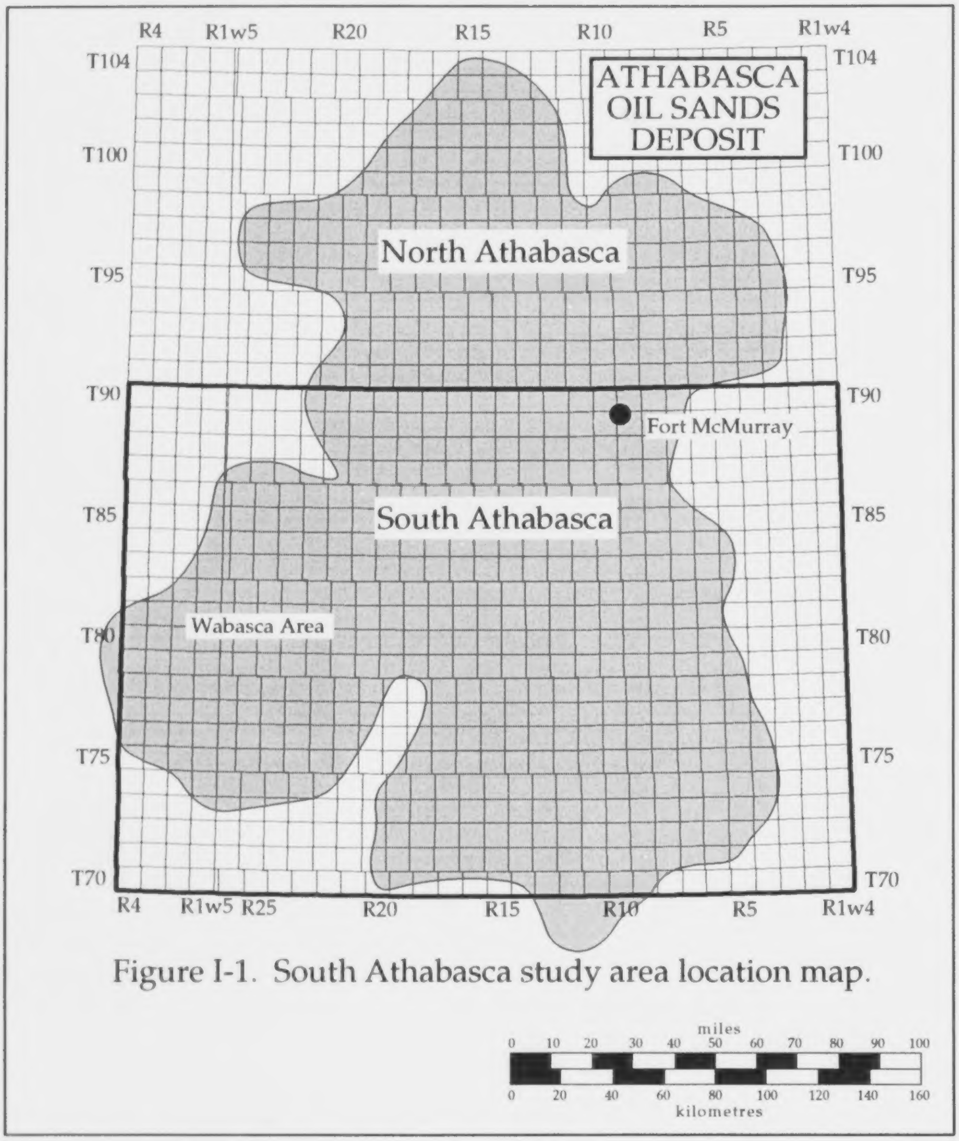
R4
R1w5
R20
R15
R10
R5
R1w4
T104
T100
T95
T90
T85
T80
T75
T70
ATHABASCA OIL SANDS DEPOSIT
North Athabasca
Fort McMurray
South Athabasca
Wabasca Area
R4
R1w5
R25
R20
R15
R10
R5
R1w4
miles
0
10
20
30
40
50
60
70
80
90
100
0
20
40
60
80
100
120
140
160
kilometres

Figure I-1. South Athabasca study area location map.

Given the perceived complexity of the stratigraphy and the apparent difficulties in correlation, it was evident that small study areas supported by only a limited database were inadequate to identify the principal stratigraphic features of the McMurray Formation. It was therefore proposed that the acquisition and analysis of a very large database of well logs and core descriptions could reveal significant stratigraphic horizons and sedimentological trends, either through simple observation using advanced digital displays, or through the use of statistical techniques.

In a formal, statistical sense, "significance" is always directly dependent on the number of samples or observations of a population. With this in mind, data was collected from as many wells as possible (but limited to a maximum density of one well per section), over a wide regional area (Fig. I–2). This data density and the size of the regional study area are much larger than that of any previous published study, and if it were possible to discern a regional stratigraphic scheme for the McMurray Formation, this approach seemed to have the highest potential for success.

The secondary objective of this thesis was to document and interpret the sedimentology of the Wabiskaw Member of the Clearwater Formation, a minor, but nonetheless economically important bitumen reservoir of the Athabasca Deposit.

In recent years many other well-known and well-studied shallow marine formations that are prolific reservoirs in the Western Canada Basin have undergone a new interpretation based on the realisation that sea-level fluctuations are intrinsic to the development of stratigraphic sequences. In studies of the Viking and Cardium Formations, for example, it has been recognised that on a regional scale these units consist of a series of stacked (or somewhat offset) prograding shoreface deposits developed during sea-level highstand (Plint et al., 1986; Walker and Eyles, 1988; Walker and Plint, 1992; Boreen and Walker, 1991). These highstand "systems tracts" generally consist of coarsening upwards and sandier upwards "parasequences" which are subsequently modified during sea-level lowstand. This modification may consist of the development of pedosols, rooted zones or coal marshes, and minor erosion surfaces or, more dramatically, by incised valleys, the geometry of which is related to the amount and rate of sea-level drop.

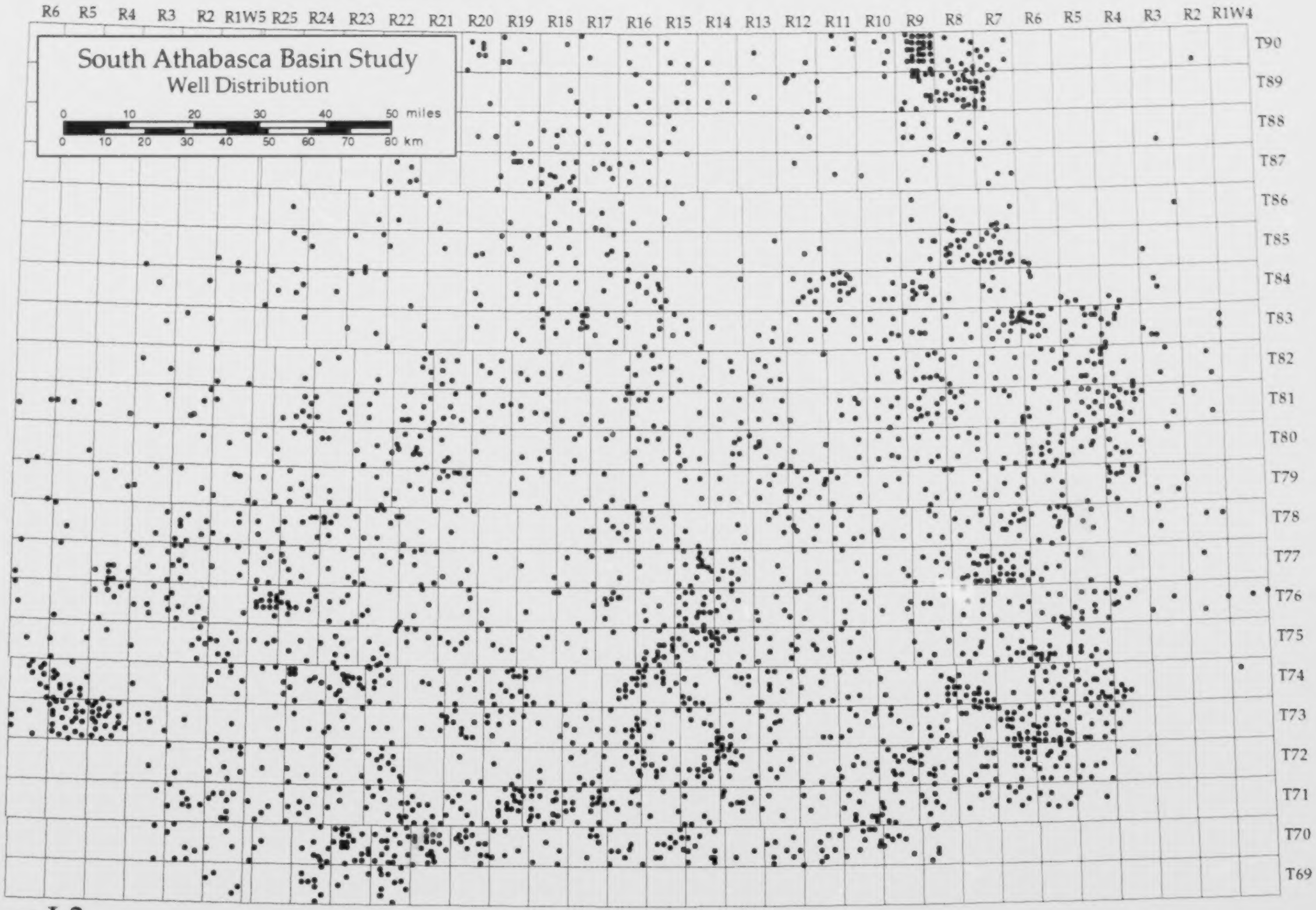
South Athabasca Basin Study
Well Distribution
0 10 20 30 40 50 miles
0 10 20 30 40 50 60 70 80 km
R6
R5
R4
R3
R2
R1W5
R25
R24
R23
R22
R21
R20
R19
R18
R17
R16
R15
R14
R13
R12
R11
R10
R9
R8
R7
R6
R5
R4
R3
R2
R1W4
T90
T89
T88
T87
T86
T85
T84
T83
T82
T81
T80
T79
T78
T77
T76
T75
T74
T73
T72
T71
T70
T69

Figure I-2

Subsequent sea-level rise typically initiates an estuarine environment, accompanied by filling of the incised valley. This is followed by sea-level transgression over the now modified highstand systems tract, which may result in a transgressive surface of erosion.

Basic to this interpretation however, is the realisation that there is a "regional" or "background" stratigraphic signature, the highstand systems tract, which is distinctive and laterally persistent, and whose regional development can be readily traced. This background signature may be correlated using geophysical well logs. Once a regional background signature has been recognised, the overprint of the lowstand systems tract and the transgressive erosion can then be easily differentiated. Thus each of the two systems tracts can be mapped separately. This system of interpretation has proven valuable for revealing the typically complex anomalies in the stratigraphy of a depositional unit. It is just such anomalies as deep sand-filled incised valleys or transgressive conglomeratic erosive lags that often form the most attractive exploration targets for the petroleum industry.

In this thesis it is shown that this system of background regional stratigraphy, overprinted by lowstand systems tracts can also be recognised in the McMurray Formation of the Athabasca Deposit. Here however, the lowstand systems tracts dominate the stratigraphic package, and the parasequences are rarely thicker than about 12 metres. For this reason, preservation of the regional prograding shoreface parasequences is less common, and their existence has not been previously been recognised.

One hundred and twenty six cores were examined in the course of the facies study of the McMurray Formation. It became obvious early in this stage of the research that the facies were too numerous and complex to be classified by sight alone. This was especially apparent when the detailed ichnofossil observations were included in the facies descriptions. To handle the facies classifications and interpretations in an objective manner, a statistical approach was necessary. A method using a combination of cluster analysis and Markov analysis was adopted and refined using, as a control, data from an existing facies study of the Bluesky Formation, a stratigraphic unit that is the lithostratigraphic equivalent to the McMurray Formation. The method and the controlled study were accepted for publication (Ranger and Pemberton, 1991) and are described in chapter IV.

All of the sedimentological data for the McMurray Formation were subsequently recorded in digital form on a microcomputer. The results of the digital facies analysis mesh well with the parasequence correlations provided by the geophysical well logs, and provide a new detailed stratigraphic framework for the McMurray Formation (chapter V).

In the other reservoir of the Athabasca Deposit, the Wabiskaw Member of the Clearwater Formation, coarsening upwards sandy lithosomes are preserved with no evidence of extensive channel incision, and this makes its stratigraphy much simpler to map and interpret. A detailed description of the Wabiskaw reservoir in the Wabasca area as well as new evidence of its paleogeographic setting is presented in chapter VII.

In addition to the regional interpretations, several detailed investigations are included in this thesis (chapters II, III, and VI). These include a facies study of the Wabiskaw "C" sand and of reservoir-quality estuarine channel sands in the subsurface McMurray Formation. These studies have been published as contributions to core workshops (Ranger and Pemberton 1988; Ranger, Sharpe and Pemberton 1988; Ranger and Pemberton 1992).

To produce the new interpretations presented in this thesis, a data base of digitised geophysical logs from over 1700 wells proved invaluable. These data were utilised in a specially written microcomputer program that was used to display and correlate the digitised logs in cross-section, and to automatically tabulate the correlated horizons. The program allows the display of many different vintages of log data in a standardised manner, to any scale, and in cross-section through any direction. The mirror image log display, used extensively in this study, also proved to be a key tool for the interpretations presented here.

The digital data base provided the capability for producing a resource inventory of the south Athabasca Deposit, and this is presented in chapter IX. The density of collected data (up to one well per square mile) allowed the inventory to be prepared in greater detail than has ever been available before.

One key piece of information that characterises the deposit is the structural elevation of the bitumen-water contact. When this horizon was mapped in the course of preparing the resource inventory, it displayed a trend dipping to the southwest almost, but not quite, parallel to the regional stratigraphic dip of the reservoir. It was immediately apparent that this had profound implications for the trapping, timing and migration history of the bitumen. The results of this research were presented orally in conference proceedings (Ranger and Pemberton, 1992), and are included in chapter VIII.

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CHAPTER II

MARINE INFLUENCE ON THE McMURRAY FORMATION IN THE PRIMROSE AREA[1]

INTRODUCTION

The Lower Cretaceous McMurray Formation of northeastern Alberta (Fig. II-1) is the reservoir for what is the single largest accumulation of hydrocarbons in the world, with in-place reserves estimated at over 900 billion barrels of bitumen (ERCB, 1981). Because hydrocarbon trapping appears to be predominantly facies controlled (Mossop, 1980), the nature of the depositional environment has been a topic of research for many decades. In the subsurface, sedimentologists examining core are struck immediately by the multitude of facies that vary considerably both laterally and vertically. A consequence of this is the apparent lack of correlatable lithostratigraphic units that can be recognised beyond even a local study area in the subsurface. For surface outcrop in the Ft. McMurray area, Carrigy's (1959) threefold subdivision of the McMurray Formation into upper, middle and lower members appears to be a workable scheme. However the fact that these units remain informal is probably a consequence of the failure to extend the recognition of these units into the subsurface over a regional area with any reliability. This is a difficult exercise even in the area adjacent to the outcrop belt (Flach, 1984).

Knight *et al.* (1981) have summarised the stratigraphic nomenclature from several studies. Although most (but not all) of these schemes use a threefold subdivision, it is by no means clear that they are correlatable units. In fact, different workers use different criteria for the subdivision, including outcrop geometry and grain size (Carrigy, 1959), radioactive markers (Nelson and Glaister, 1976) and facies interpretation (James, 1977; Knight *et al.*, 1981).

No attempt is made is this study to subdivide the McMurray Formation into major lithostratigraphic units, but rather to demonstrate that the

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[1] A version of this chapter has been published. Ranger, M.J. and Pemberton, S.G. 1988. Marine influence on the McMurray Formation in the Primrose area, Alberta. *In:* James, D.P. and Leckie, D.A. (eds), Sequences, stratigraphy, sedimentology: surface and subsurface. Canadian Society of Petroleum Geologists, Memoir 15, pp. 439-450.

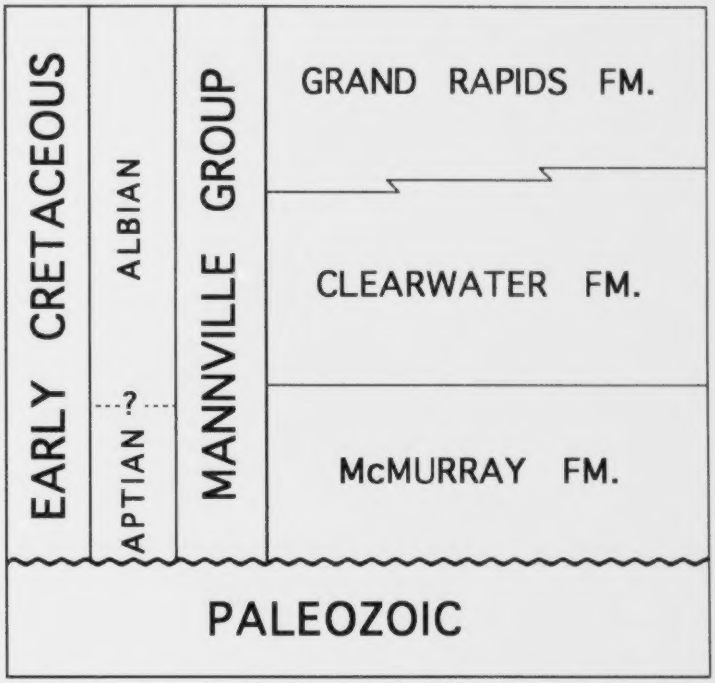

EARLY CRETACEOUS
ALBIAN
?
APTIAN
MANNVILLE GROUP
GRAND RAPIDS FM.
CLEARWATER FM.
McMURRAY FM.
PALEOZOIC

Figure II-1. Stratigraphy of the McMurray Formation.

complex lithostratigraphy appears to be a consequence of marine transgression up a mature drainage valley system, and that the topography of this system affected the distribution of depositional environments even at the top of the McMurray interval.

Flach and Mossop in several joint and separate studies (e.g. Mossop, 1980; Mossop and Flach, 1983; Flach, 1984; Flach and Mossop, 1985) have demonstrated that in outcrops along the Steepbank River the middle McMurray consists entirely of fill in a deep migrating channel. Although they consider this channel to be dominantly fresh water fluvial in origin with only minor marine influence (Flach and Mossop, 1985), ichnofossil studies have shown a significant marine influence on the same rocks (Pemberton *et al.*, 1982). Ichnofossil evidence strongly suggests that the Steepbank River outcrops were deposited in a brackish estuarine setting, and that the channel may represent an excellent example of an ancient estuarine channel environment (Pemberton *et al.*, 1982). Workers north (basinward) of the Steepbank River outcrops (James, 1977; Rennie, 1987) have also recognised a marine influence, certainly in the upper part of the McMurray and, significantly, also throughout much of what would correspond to the middle McMurray at Steepbank. These have been interpreted variously as estuarine and/or marginal marine (Rennie, 1987) and nearshore and interdistributary bay deposits (James, 1977).

South of the Steepbank River outcrops, Nelson and Glaister (1976) interpreted the existence of marine interdistributary environments including beaches, offshore bay and offshore transition grading into a distributary system, throughout the entire McMurray Formation. Of note is the fact that their sand-dominated distributary system is well developed to the northeast, and they imply more marine conditions to the southwest.

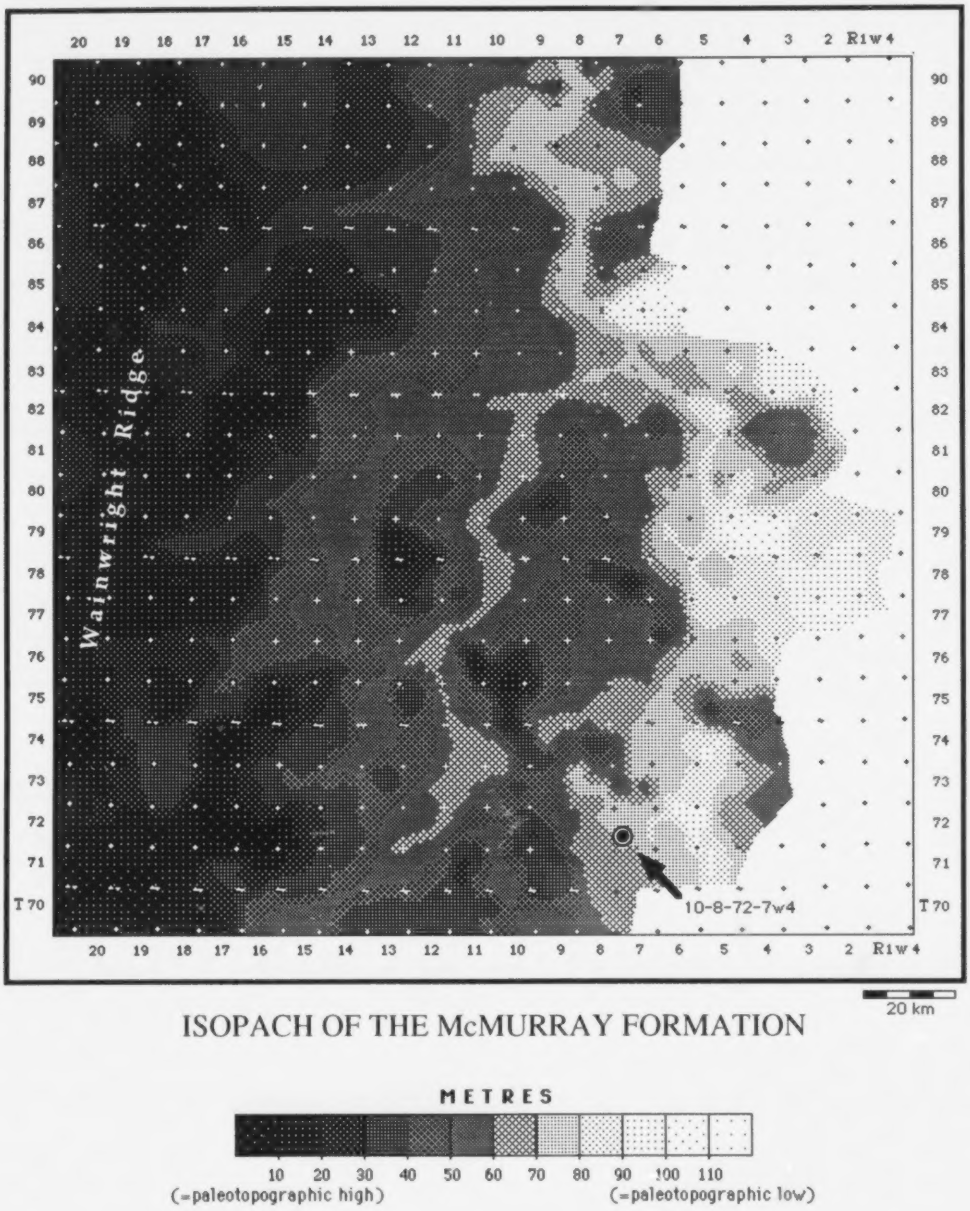
Immediately to the east of that study, Knight *et al.*, (1981) interpreted the upper part of the McMurray, their unit 2, as occurring in an offshore to nearshore marine environment.The lower 25 metres of their core is cross-stratified and rippled silty sand which they interpret to be either distributary or estuarine channels, possibly stacked.

This study will show that there is indeed a persistent marine influence throughout much of what probably corresponds to the upper and middle members of the McMurray Formation, at least as far south as the Primrose area in township 70 to 72. Much of this influence is probably in the form of brackish estuarine conditions, and there is strong evidence that the distribution of the estuarine environments is directly related to underlying topography on the sub-Cretaceous unconformity.

BASIN PALEOTOPOGRAPHY

The McMurray Formation lies directly on a basement of well-lithified Devonian carbonates that subcrop at the sub-Cretaceous unconformity. There can be no doubt that the drainage valley topography must have played an important role in the distribution of subsequent depositional environments. Reconstructing the paleotopography on the unconformity can be accomplished by mapping the thickness of a suitable lithostratigraphic unit that lies directly on the unconformity, thus producing a "mould" of the underlying erosional paleotopography (Williams, 1963; Ranger, 1984). This effect can be created here using an isopach map of the McMurray Formation (Fig. II-2). The map covers most of the area of the Athabasca Oil Sands Deposit south of Fort McMurray. Two major features that influenced the paleotopography are expressed on the map. The Wainwright Ridge is a north-northwesterly trending paleotopographic high consisting of resistant carbonates of the Upper Devonian Winterburn Group (Williams, 1963). It is expressed on the western side of McMurray isopach map by a thinning, in some areas to less than 10 metres. To the east, the solution of middle Devonian evaporites along a front parallel to the outcrop of the Precambrian shield (DeMille *et al.*, 1964; Vigrass, 1966; Carrigy, 1967) resulted in structural subsidence contemporaneous with erosion on the sub-Cretaceous unconformity. This structural low apparently localised a major north-northwesterly flowing trunk drainage system (Carrigy, 1963, 1967), herein referred to as the McMurray channel valley (equivalent to the McMurray "trough" of Mossop, 1980). The expression of this feature is the thickening of the McMurray Formation on the east side of the isopach map (Fig. II-2).

Details of the McMurray isopach map are interpreted to represent a system of northeastward flowing valleys eroded into the sub-Cretaceous unconformity, which were tributaries to the main north-northwesterly


20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 R1w4
90
89
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84
83
82
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80
79
78
77
76
75
74
73
72
71
T 70
Wainwright Ridge
10-8-72-7w4
20 km
ISOPACH OF THE McMURRAY FORMATION
METRES
10 20 30 40 50 60 70 80 90 100 110
(=paleotopographic high)
(=paleotopographic low)

Figure II-2. Basin paleotopography of the southern Athabasca oil sands deposit. Gray shading is an isopach map of the McMurray Formation, providing an interpretation of the erosional topography on the underlying sub-Cretaceous unconformity. A system of long, narrow tributaries had their headwaters in the southwest on the Wainwright Ridge and drained into a main trunk valley, the McMurray channel valley system.

trending trunk drainage valley. Carrigy (1967) was the first to map the major elements of this drainage system, but the computer techniques and much greater well control available today yield finer detail.

This inferred paleotopography has important consequences for the interpretation of the depositional environments of the McMurray Formation. Much of the McMurray Formation represents deposition during the first major Lower Cretaceous (Aptian) eustatic sea-level rise. During transgressive phases, marine waters would have flooded the intricate tributary system. One can envisage a complex interaction of physical, chemical and biological factors including: 1) brackish waters, 2) restricted marine access, 3) a seasonal and tidal salt wedge migrating upstream and downstream, 4) stressful habitats allowing only a very restricted flora and fauna, 5) shifting geochemical conditions at the sediment-water interface, and 6) sediment aggradation due to a decrease in gradient of the drainage system. Using core from a well in the Primrose area, 10-8-72-7W4, the possible effects of many of these factors can be demonstrated, and it is suggested that this accounts for much of the facies complexity of the McMurray sediments. This core is from an area that was in one of the tributary channels but probably not far from the trunk drainage valley (Fig. II-2), although the exact location of the trunk valley is obscure due to erosion of the McMurray Formation to the east.

SELECTED FACIES DESCRIPTIONS

The facies developed in the example well are complex and relatively thin (49 facies transitions were logged in 36 metres of core). Not all of the facies recognised are described here, but several with very significant physical or biogenic characteristics are discussed. The core does not fully penetrate the McMurray Formation, but ends about 17 m above the sub-Cretaceous unconformity (Fig. II-3). Throughout the core, cross-stratified sands indicate dominantly oscillatory flow conditions (Fig. II-7a). Current ripples (Fig. II-7d) are relatively rare.

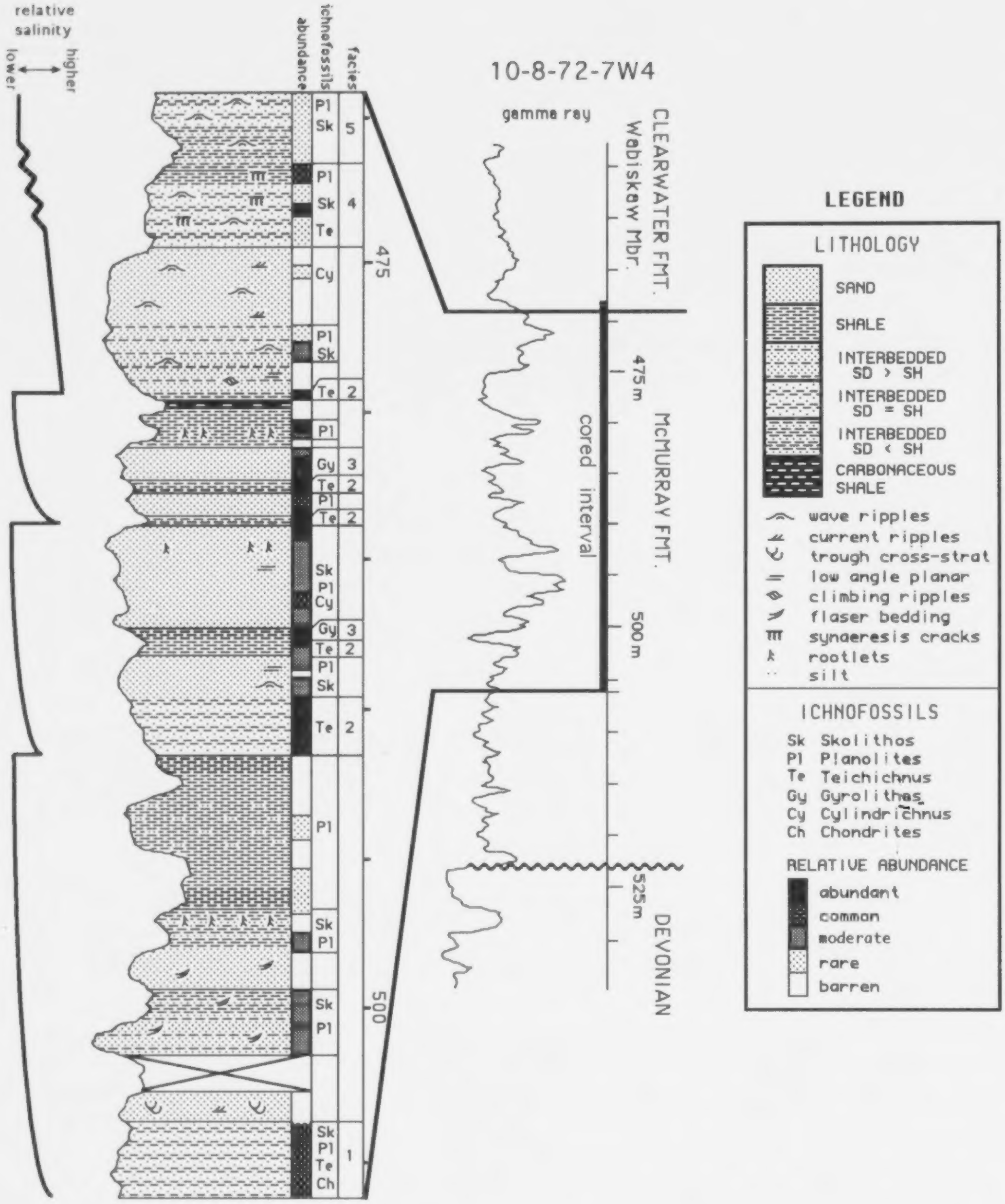

10-8-72-7W4
relative salinity
lower
higher
ichnofossils
abundance
facies
gamma ray
CLEARWATER FMT.
Wabiskaw Mbr.
McMURRAY FMT.
DEVONIAN
cored interval
475
500
475 m
500 m
525 m
Pl
Sk
Te
Cy
Gy
Ch
1
2
3
4
5
LEGEND
LITHOLOGY
SAND
SHALE
INTERBEDDED SD > SH
INTERBEDDED SD = SH
INTERBEDDED SD < SH
CARBONACEOUS SHALE
wave ripples
current ripples
trough cross-strat
low angle planar
climbing ripples
flaser bedding
synaeresis cracks
rootlets
silt
ICHNOFOSSILS
Sk Skolithos
Pl Planolites
Te Teichichnus
Gy Gyrolithes
Cy Cylindrichnus
Ch Chondrites
RELATIVE ABUNDANCE
abundant
common
moderate
rare
barren

Figure II-3. Descriptive log of the display core, 10-8-72-7W4.

Facies 1

The bottom of the core (503 to 506.5 m) penetrates a zone that on the gamma ray log has a serrated blocky appearance, which, given no other information might suggest a channel sand. In core, this constitutes an interbedded very-fine sand and silty shale. Bed thicknesses are on the order of 1 to 10 cm (thin-bedded), but interlaminated sand-shale horizons a millimetre or so in thickness are widespread (Fig. II-4c). Small scale unidirectional current ripples are present, but rare. Bioturbation is very common and partly obscures the physical structures. Of note is the pattern of bioturbation. Only a few ichnogenera are present, predominantly *Skolithos* and *Planolites* in the sand, with *Planolites* and less commonly *Teichichnus* in the shale. These ichnofossils are conspicuous for their abundance yet low diversity and small size. *Skolithos* is rarely over a centimetre long, and *Planolites* is rarely larger than a millimetre in diameter (Fig. II-4c).

This ichnofossil suite has all the characteristics of brackish water assemblages recognised in modern (Howard and Frey, 1973, 1975) and ancient (Pemberton *et al.*, 1982; Wightman *et al.*, 1987) environments. These characteristics include: 1) low diversity, 2) typically marine forms (rather than a mixed marine-nonmarine assemblage), 3) forms that represent a simple feeding strategy, 4) diminished size, and 5) although the presence of individual forms is not important, elements of both the *Skolithos* and *Cruziana* ichnofacies are commonly present (Wightman *et al.*, 1987).

Facies 2 (*Teichichnus* beds)

A distinctive heavily bioturbated facies occurs at several intervals in the core, varying in thickness from 50 cm to 1.25 m. (e.g. 490-491.25 m). These are generally silty shales with some centimetre-thick bioturbated sand intervals. Again, this facies is distinctive for its ichnofossil suite, which consists almost exclusively of small *Teichichnus* burrows, 2 to 3 cm in transverse section and 5 mm or less in longitudinal section (Fig. II-4d). The burrows are so abundant that individual forms are not readily discernible, but the overlapping spreiten give a distinctive appearance to the strata (Fig. II-4d). Sandwiched between these extremely burrowed zones are 3 to 4 cm thick

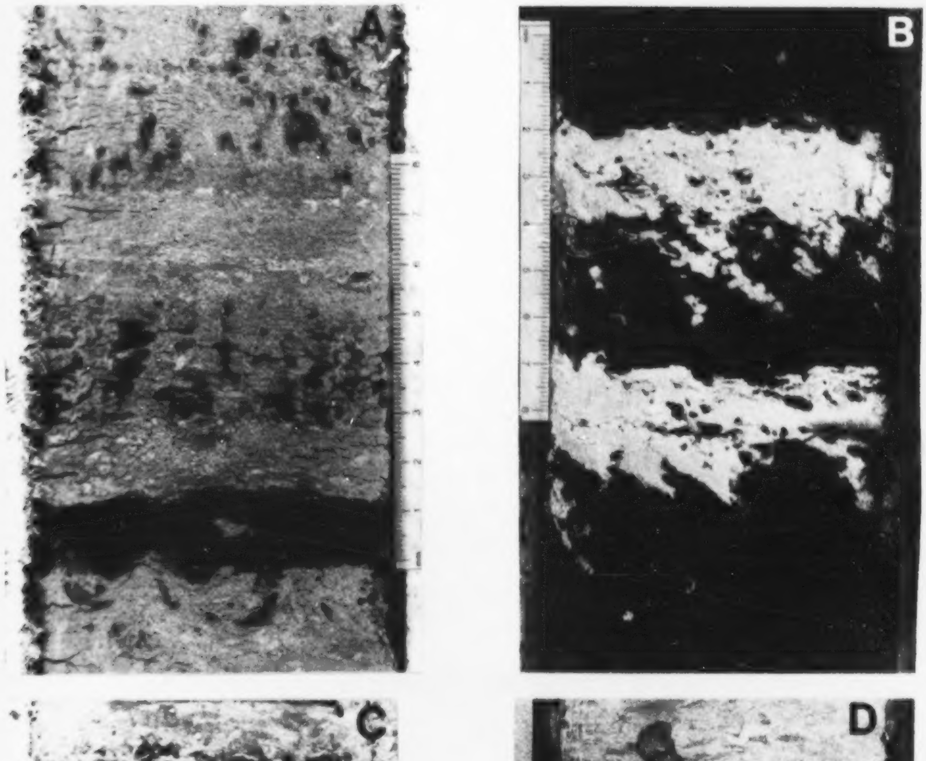
Figure II-4. Examples of facies in the example well (10-8-72-7W4). Lighter lithology is shale; sand is bitumen-stained and dark.

A. *Gyrolithes* in interbedded sand and shale 10-8-72-7W4 (facies 3: 487.6 m).

B. Inclined *Gyrolithes* 10-33-72-7W4.

C. Facies 1: diminutive *Planolites* and *Skolithos* in interbedded and laminated sand and shale 10-8-72-7W4 (503.3 m).

D. Abundant, monospecific, diminutive burrowing of a deposit-feeder (*Teichichnus*) in silty shale 10-1-72-7W4 (484.75 m).


A
B
C
D

shale intervals that are totally barren of biogenic activity (e.g. at 492.5 m, Fig. II-5d). They have a sharp base, and are increasingly bioturbated toward the top. This must record a sudden event that proved inhospitable for the *Teichichnus* tracemaker. The composition of the sediment is essentially the same throughout, the shale recording a rather passive low energy environment, with minor influxes of silt, so it is unlikely that this records a storm event or other energy related anomaly. *Teichichnus* is typically found in marine environments. As discussed in the description of facies 1, the great abundance, low diversity, and diminished size, all characteristics that reach an extreme in this facies, suggest that this was a stressed brackish niche that could support only a specialised infauna with a simplistic feeding behaviour. Because of the rather homogeneous nature of the sediment and burrowing it can be surmised that there was little fluctuation in salinity or energy levels. The only exception is the thin zones of barren shale which might represent sudden salinity changes. An invasion of fresh water conditions is the favoured interpretation, because marine water would probably bring a temporary influx of opportunistic species, for which there is no evidence in the core.

Facies 3 (*Gyrolithes* beds)

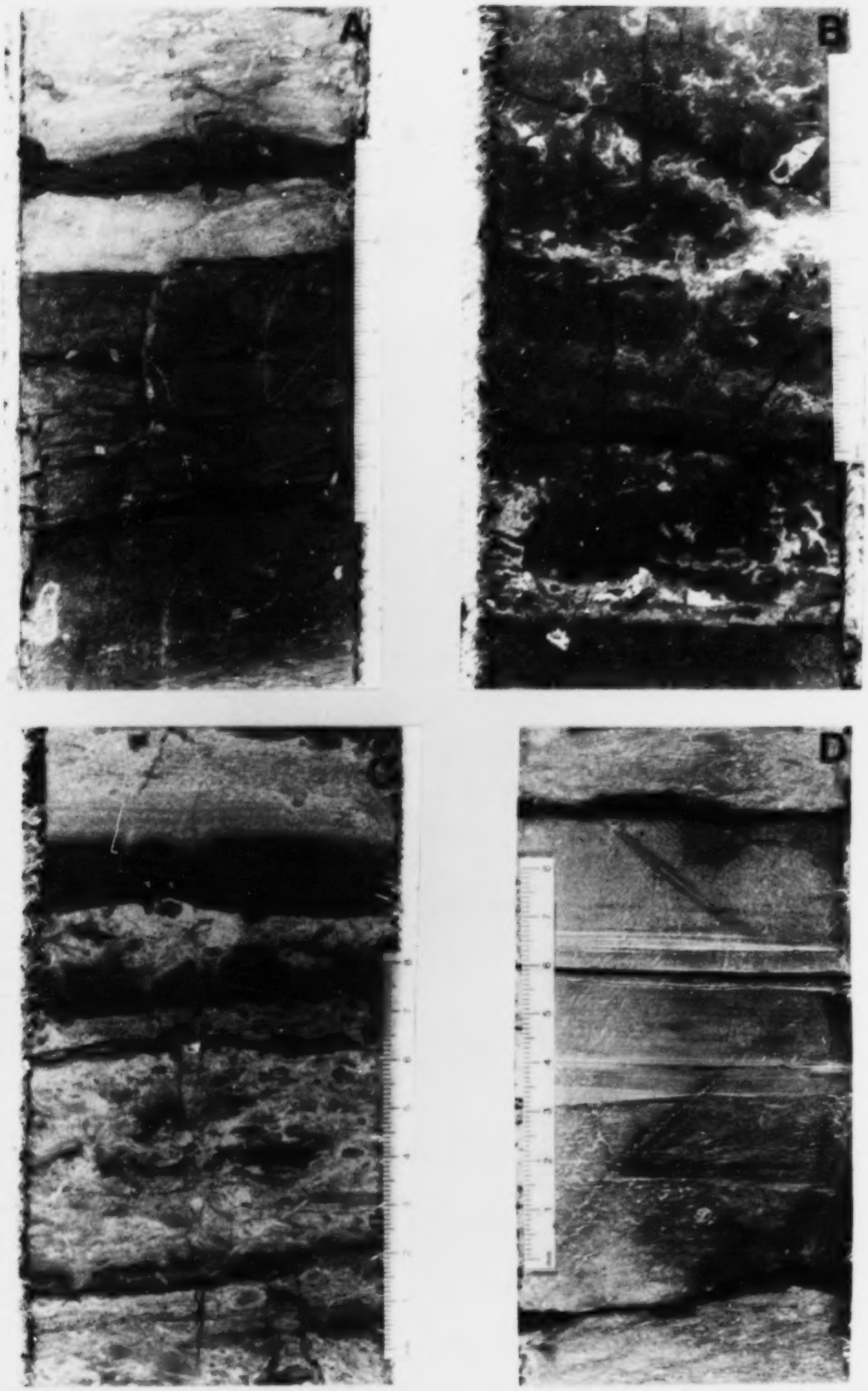
Lithofacies 3 consists of interbedded sand and shale. Bed thickness ranges from 1 to 10 cm, and the shale content varies from 40 to 80%. The shales are typically highly bioturbated, and the burrows normally extend into the sand from shales above. The ichnofossil suite is monospecific, composed entirely of *Gyrolithes*, which is a corkscrew-shaped burrow that appears in core as a series of offset circles or ovals (Figs. II-4a, II-4b). It probably represents the dwelling burrow of an annelid that exhibits this very specialised burrowing behaviour to seek refuge from rapid bottom water salinity fluctuations. (Gernant, 1972; Powell, 1977)

Facies 4 (synaeresis cracked)

This distinctive, relatively thick facies (e.g. 472.5 - 475 m) appears persistent from well to well in the Primrose area. The lithology consists of

Figure II-5. Examples of facies in the example well (10-8-72-7W4).

A. *Teichichnus* bed (facies 2) abruptly overlying carbonaceous shale; a possible example of flooding surface in an estuarine setting (480 m).
B. Intense monospecific burrowing (*Palaeophycus*) (489 m).
C. Storm beds (sharp base, fining upwards, non-bioturbated) in intensely bioturbated shale (490.3 m).
D. Non-bioturbated laminated shale sandwiched between intensely bioturbated *Teichichnus* beds (monospecific, diminished size), suggesting salinity fluctuations (492.5 m).


A
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interbedded very-fine sand and shale. Bed thickness varies from less than 1 cm to about 5 cm. The proportion of shale varies from about 60% at the top and base of the interval, to 30% in the middle. The sands are commonly cross-bedded, and this appears to result exclusively from oscillatory wave ripples. This facies is characterised by synaeresis cracks, which are abundant in most of the thin shale beds (Fig. II-6).

Bioturbation is minimal, consisting almost exclusively of *Planolites*, and is noticeably absent from the beds with synaeresis cracks.

Wightman *et al.* (1987) have recently discussed the significance of synaeresis cracks, pointing out that crenulated forms in the absence of load casts imply formation at the sediment-water interface due to fluctuations in salinity. A similar interpretation can be made for this facies, which fits the context of an estuarine environment of fluctuating salinities. The non-bioturbated, synaeresis-cracked shale beds represent fresh water deposits and are periodically flooded by saline waters, which cause a shrinkage in the volume of the clay in the shallow substrate and may support a temporary infauna.

Facies 5 (restricted anoxic)

Throughout the Primrose area the uppermost facies of the McMurray Formation consists of 2 to 3 metres of interbedded shale and very-fine sand. The proportion of shale and the bed thickness varies from well to well, but shale dominates at 70 to 80% in the 10-8-72-7W4 well and bed thickness is in the range of a few centimetres. The sand is cross-stratified and these appear to be exclusively oscillatory wave ripples. The shale is dark brown apparently due to a high organic content. Bioturbation is rare (Fig. II-6a), and restricted to a few *Planolites* burrows.

The high organic content and general lack of bioturbation suggest that this facies is the result of very restricted, predominantly anoxic conditions.

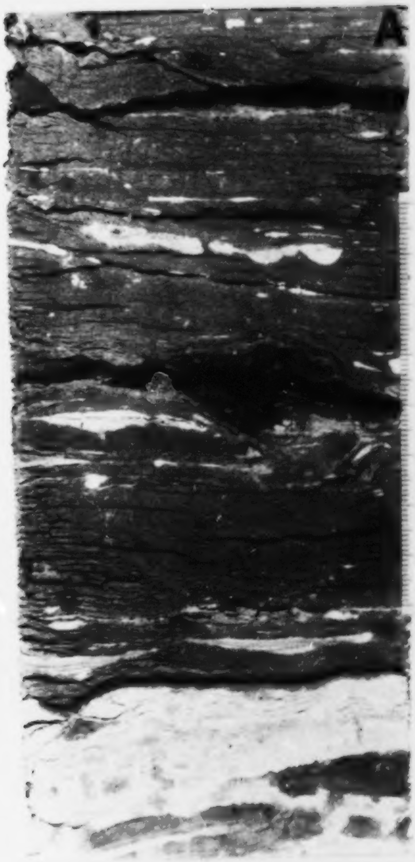
FLOODING SURFACES

Rooted zones occur at 3 levels in the core (497.5, 484.0 and 480.5 m). A carbonaceous shale occurs at 480 m (Fig. II-5a), probably associated with the

Figure II-6. Examples of facies in the example well (10-8-72-7W4).

A. Non-burrowed dark brown organic shale with silt lenses suggests anoxic conditions (base of facies 5: 471.8 m).

B. Synaeresis cracks in laminated sand and shale (474 m). Note that cracks occur dominantly in non-bioturbated shales and extend from bioturbated horizons - interpreted to result from salinity fluctuations.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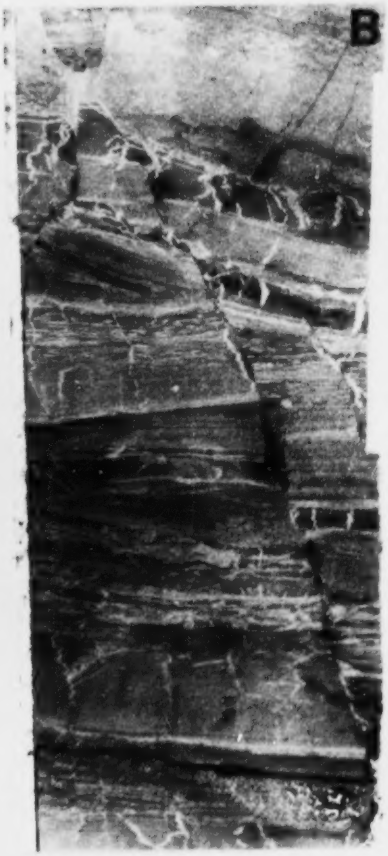

B

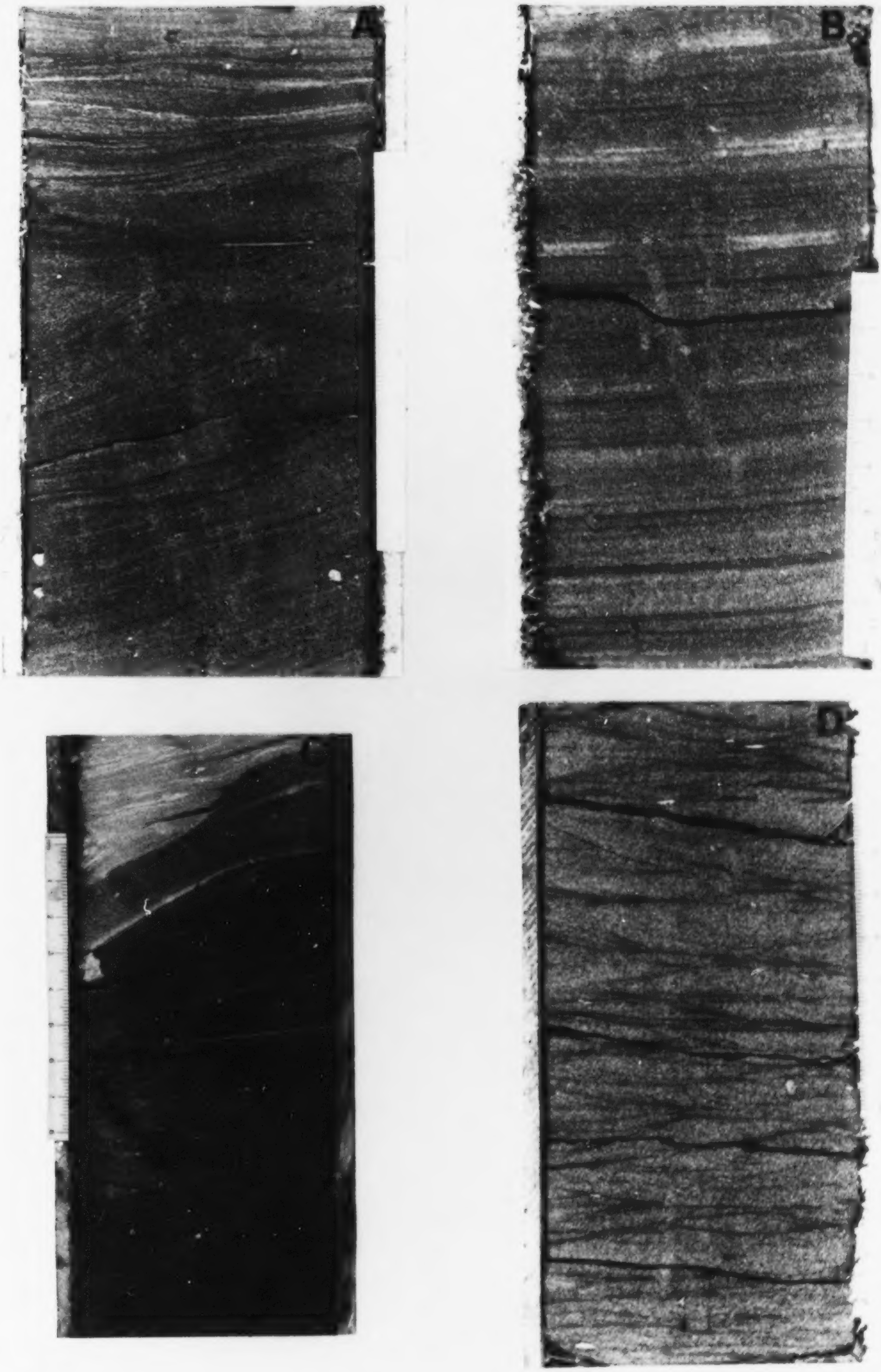
Figure II-7. Examples of facies in the example well (10-8-72-7W4).

A. Cross-stratification due to dominantly oscillatory flow (waves) (488.7 m).

B. Escape structures in planar laminated sand(479.9 m).

C. Oscillatory flow (wave) cross-stratification (10-33-72-7W4, 472.9 m).

D. Trough cross-stratification indicating unidirectional (current) flow (502.9 m).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uppermost rooted zone. The rooting is for the most part subtle yet noticeable due to a few vertical coaly filaments and abundant associated carbonaceous debris. The upper two rooted zones are overlain abruptly by facies 2, the *Teichichnus* beds. The lowermost rooted zone is overlain by 3 metres of laminated fissile shale that is almost entirely barren of ichnofossils. This barren interval is abruptly overlain by the *Teichichnus* beds of facies 2. These contacts may well be examples of flooding surfaces in an estuarine setting and could represent a starting point for a sequence interpretation of the McMurray Formation.

DISCUSSION

The displayed core is typical of the succession found throughout the upper to middle sections of the McMurray Formation in the Primrose Area. It is dominated by physical and biogenic features that point to the presence of brackish water conditions and fluctuating salinities. During middle McMurray time, early in the Aptian transgression, a marine shoreline probably existed in the vicinity of the present day Steepbank River outcrop belt (Pemberton *et al.*, 1982). Assuming that the McMurray Formation at Steepbank is approximately coeval with that in the Primrose area, then pulses of the marine influence were being felt some 200 km south (landward) up the paleodrainage system before fully marine conditions resulted in the development of the overlying Clearwater Formation. The effect of the inherent topography should be taken into account in any depositional model. The detailed paleotopography that is beginning to unfold fits well with the sedimentological data, and is certain to be a key element in a comprehensive interpretation of these complex facies patterns.

While there can be little doubt of the marine influence on the sediments, one should not become enmeshed in a discussion of whether this represents "estuarine" conditions or not. The definition of an estuary is a controversial one (Schubel and Pritchard, 1971). Fairbridge (1968) defined an estuary as a semi-enclosed marginal-marine body of water in which salinity is measurably diluted by fluvial discharge. However, Howard and Frey (1975a, 1975b) have studied "salt marsh estuaries" that have little or no fresh water input but are dominated by tidal processes. The presence of a tide is sometimes cited as a necessary prerequisite for an estuary (Clifton, 1982; Flach and Mossop, 1985), given that the word estuary comes from the Latin "aestus" meaning "tide". There is, however, no such thing as a totally tideless coast and this definition therefore requires an indication as to how much tidal influence constitutes estuarine conditions. While it is true that tidal range is often amplified in an embayment, the magnitude of the amplification depends on embayment geometry and, if the tidal range is small to begin with, tidal ranges in the embayment may not be significantly higher.

Nonetheless, mixing of marine and fluvial waters can occur without significant tides (Schubel and Pritchard, 1971). It is suggested that this is especially so where the evidence shows that transgressive conditions are actively drowning a river valley. If a small tidal volume is present (relative to fluvial flow) it is likely to be recorded by the chemical and biological consequences of a discrete migrating salt wedge (Pritchard and Carter, 1971). It is just such chemical and biogenic effects that appear to be recorded in the McMurray cores from the Primrose area.

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CHAPTER III

THE SEDIMENTOLOGY AND ICHNOLOGY OF ESTUARINE POINT BARS IN THE McMURRAY FORMATION OF THE ATHABASCA OIL SANDS DEPOSIT, NORTHEASTERN ALBERTA, CANADA[1]

INTRODUCTION

The McMurray Formation of the Athabasca Oil Sands Deposit in northeast Alberta (Fig. III-1) consists of a series of depositional units that are almost certainly the result of eustatic sea-level fluctuation. It accumulated far to the east of the active orogenic belt of western North America, on the relatively stable cratonic platform and probably beyond the influence of the major tectonic subsidence of the foreland basin. The McMurray Formation rests directly on a hard substrate of Devonian carbonates that subcrop at the sub-Cretaceous unconformity. The erosional paleotopography on the unconformity reflects a regional fluvial drainage system (Ranger and Pemberton, 1988). The McMurray Formation represents the record of overall aggradational fill of this entrenched valley system, brought on by initiation of the major Cretaceous marine transgressions within the North American Interior Seaway.

Highstand systems tracts in the McMurray Formation appear to consist of prograding shoreface parasequences with a strong estuarine overprint. Where several of these parasequences are preserved in the subsurface, they appear as stacked coarsening-upwards shoreface deposits, commonly with a rooted horizon, a coal horizon or an oxidised paleosol at the top (Fig. III-2). Where preserved, the shoreface deposits provide the only correlatable stratigraphic units that can be recognised over a relatively regional area, and they can therefore be used to help establish a stratigraphic framework for at least the upper and middle part of the McMurray Formation. The lower

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[1] A version of this chapter has been published. Ranger, M.J. and Pemberton, S.G. 1992. The sedimentology and ichnology of estuarine point bars in the McMurray Formation of the Athabasca Oil Sands Deposit, northeastern Alberta, Canada. *In:* Pemberton, S.G. (ed), Applications of ichnology to petroleum exploration. A core workshop. SEPM core workshop no. 17. Calgary, pp. 401-421.

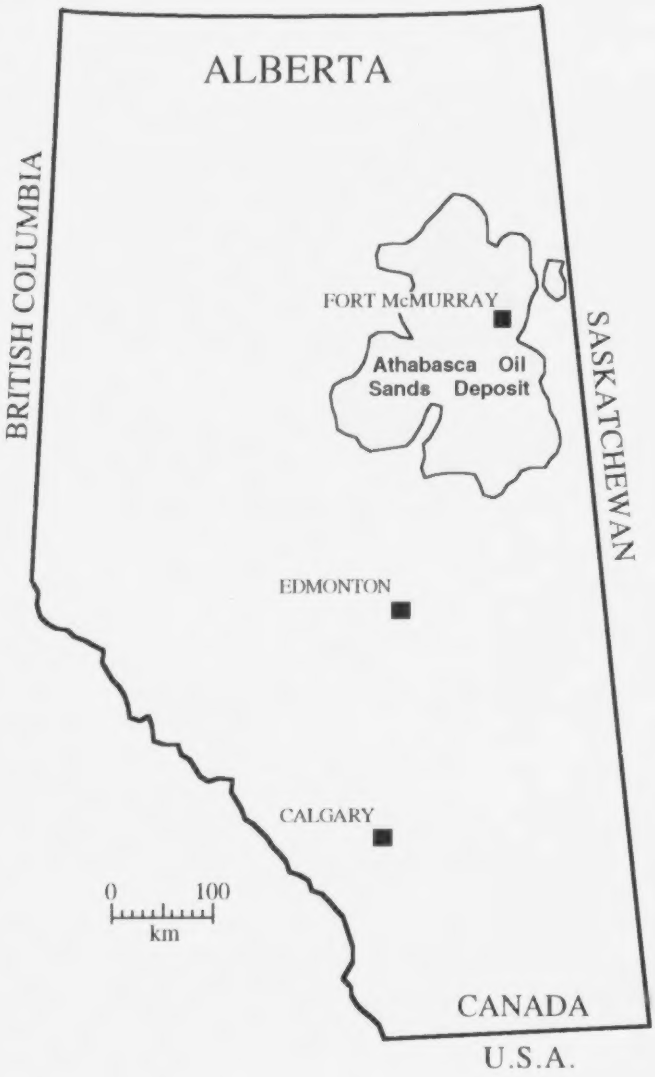

ALBERTA
BRITISH COLUMBIA
SASKATCHEWAN
FORT McMURRAY
Athabasca Oil Sands Deposit
EDMONTON
CALGARY
0
100
km
CANADA
U.S.A.

Figure III-1. Location map of the Athabasca Oil Sands.

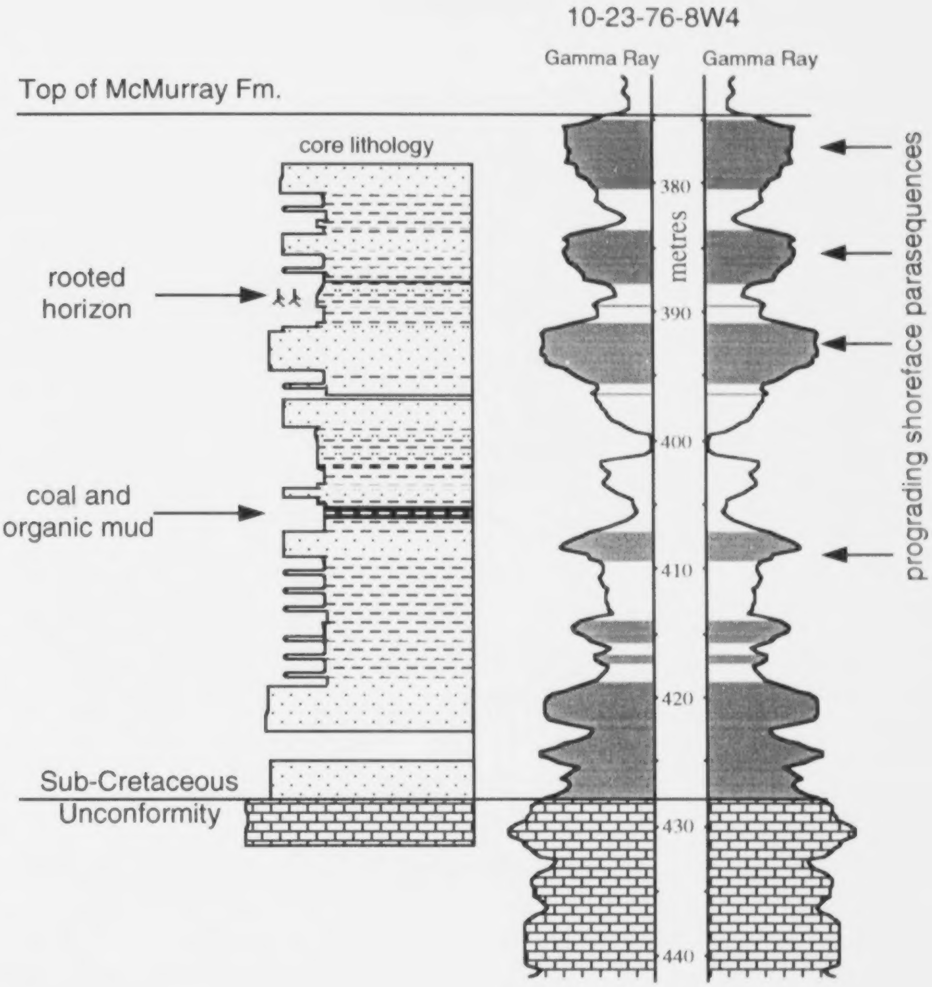

10-23-76-8W4
Gamma Ray
Gamma Ray
Top of McMurray Fm.
core lithology
rooted horizon
coal and organic mud
Sub-Cretaceous Unconformity
metres
380
390
400
410
420
430
440
prograding shoreface parasequences

Figure III-2. Gamma-ray log and lithology log for the well 10-23-76-8W4. This well penetrates a well-developed stacked succession of shoreface parasequences, commonly capped with coal or rooted horizons. Gamma ray curve in the right track is a mirror image of the left track.

McMurray is preserved only in the deepest valleys on the unconformity and it appears to be dominantly fluvial, given that no shoreface successions have yet been recognised. However, the lowstand fluvial deposits may have totally obliterated all trace of the shoreface. The deeper valley floors are more confined and, consequently, meandering fluvial point bars are more likely to have migrated from valley side to valley side, destroying all trace of earlier deposits. Therefore, because the topography on the unconformity became more subdued as the McMurray Formation aggraded, there probably exists a preservational bias for lowstand facies towards the base and highstand facies towards the top.

Because of the low gradient, valley - tributary topography in which the McMurray Formation accumulated, even minor sea-level fluctuations would have caused shoreline shifts of large magnitude. During transgressive events, marine waters would have been introduced far up the arms of the valley system, causing the development of extensive estuaries. The characteristics of these estuaries would have included establishment of a salt wedge, brackish waters in the zone of mixing, tidal effects, introduction of a faunal change, and a change in depositional dynamics. During highstand sea level a progradational shoreface was established, initially parallel to the valley walls and then progressively down the axis of the valley. The McMurray subbasin was relatively enclosed during Lower Mannville time, with a rather narrow mouth opening towards the Boreal sea to the north, confined by the Precambrian Shield on the east and the Grosmont High on the west. Because of this, dispersion and mixing of fresh water from fluvial discharge would have been constrained, and therefore brackish conditions probably remained in the basin even during highstand. This is suggested by a brackish ichnofaunal overprint on the shoreface deposits (Ranger and Pemberton, 1988).

Similarly, minor sea-level lowering would have had physiographically extensive effects, dominated by fluvial incision into the shoreface and older sediments down to base level. This was a time of extensive destruction of the highstand facies. These incised fluvial valleys then became the site once again of brackish conditions and the establishment of estuaries early in the succeeding transgression.

Minor estuarine channel fills are not easily recognised in the McMurray Formation for a number of reasons: 1) whereas fluvial channels tend to be dominated by the preserved remnants of sandy point bars, either sand or mud may dominate estuarine sediments depending on the physiographic position in the estuary; 2) estuarine sediments tend to be highly heterogeneous on a large and small scale, because of the interplay of a large number of factors e.g. tides, salinity fluctuation, rate of fluvial discharge, faunal populations, seasonal and storm changes in flow volume; 3) estuaries typically are biologically rich, and this produces an ichnological overprint that serves to destroy physical sedimentological features; and 4) the Athabasca area has undergone little subsidence, therefore younger channel systems tend to incise down into older systems, producing a complex stacking of estuarine systems of various ages.

On the other hand, the highstand shoreface parasequences form a correlatable "background" that can be readily recognised in core and even from geophysical well logs. Where the distinctive coarsening upwards signature of the parasequence is missing, it has been eroded by fluvial incision, and the fill is that of an aggrading fluvio-estuarine system.

At several times in the history of aggradation of the McMurray Formation, a major sea-level lowering occurred, producing the deepest incisions into the sedimentary succession. The most important of these appears to have occurred near the end of McMurray deposition (Mossop, 1980). This event produced deep incisions up to 40 m thick, many of which are readily recognisable in core and from well logs because they have a distinctive and typically uniform or coarsening upwards fill, attributed to point bar deposition. The best known example of this, and the site where the deep incision was first recognised is at the Steepbank River outcrop of the McMurray Formation (Mossop, 1980; Mossop and Flach, 1983; Flach and Mossop, 1985). Here, as well as at several nearby mine face exposures, the channel fill is dominated by Inclined Heterolithic Stratification (IHS). This consists of repetitive sets of decimetre to metre thick couplets of sand and mud, inclined at angles of 8° to 12°, grading into a coarse-grained trough cross-bedded sand facies towards the base (Mossop and Flach, 1983). Overlying the IHS beds are horizontally bedded, silty, argillaceous sands and muds that are extensively bioturbated. Originally interpreted as delta foresets (Carrigy, 1971), it is generally accepted that this represents lateral accretion of point bars in a channel (Mossop and Flach, 1983; Smith, 1987, 1988). Although Mossop and Flach originally believed the Steepbank IHS to represent a generally fining upwards fluvial channel system (Mossop and Flach, 1983; Flach and Mossop, 1985), subsequent ichnological and sedimentological studies (Pemberton *et al.*, 1982; Smith, 1987) indicate a strong marine influence, suggesting that the channels were indeed brackish estuarine in nature, as originally proposed by Stewart and MacCallum (1978). The estuarine channels at the Steepbank outcrop are estimated to have been 30 to 40 metres deep.

FACIES DESCRIPTION - SUBSURFACE ESTUARINE CHANNELS

Facies similar to those exposed at the Steepbank outcrop have been recognised in the subsurface in the southern part of the Athabasca Deposit and have been recovered from core. The core from well 10-29-73-5W4 in the Kirby Field penetrates a 34 m thick estuarine channel fill (Fig. III-3) whose vertical morphology is sedimentologically similar to that observed at the outcrop locations.

The base of the channel fill consists of medium to coarse-grained, current cross-bedded pebbly sand, 7 m thick with an erosional base. Brecciated shale clasts are common. This facies grades upwards to a 27 m thick unit consisting of sand and mud couplets varying in thickness from approximately 7 cm to 50 cm. Depending on the orientation of the core, the contacts between the mud and the sand beds are inclined up to a maximum apparent angle of 15°. Each couplet consists of a fine-grained sand bed whose base may be erosional, and a sharp transition up into a silty mud bed several centimetres thick. The contact is generally bioturbated with mud filled burrows penetrating down into the sand (Fig. III-4a). Incipient sideritisation is developed in many of the mud beds, especially towards their base, immediately on top of the sand. Based on the physical similarly between these couplets and outcrop examples, individual sand and mud beds are probably laterally continuous from the top of the facies unit to near the base where the mud beds gradually pinch out (or more likely have been scoured

Dome et al Kirby 10-29-73-5W4

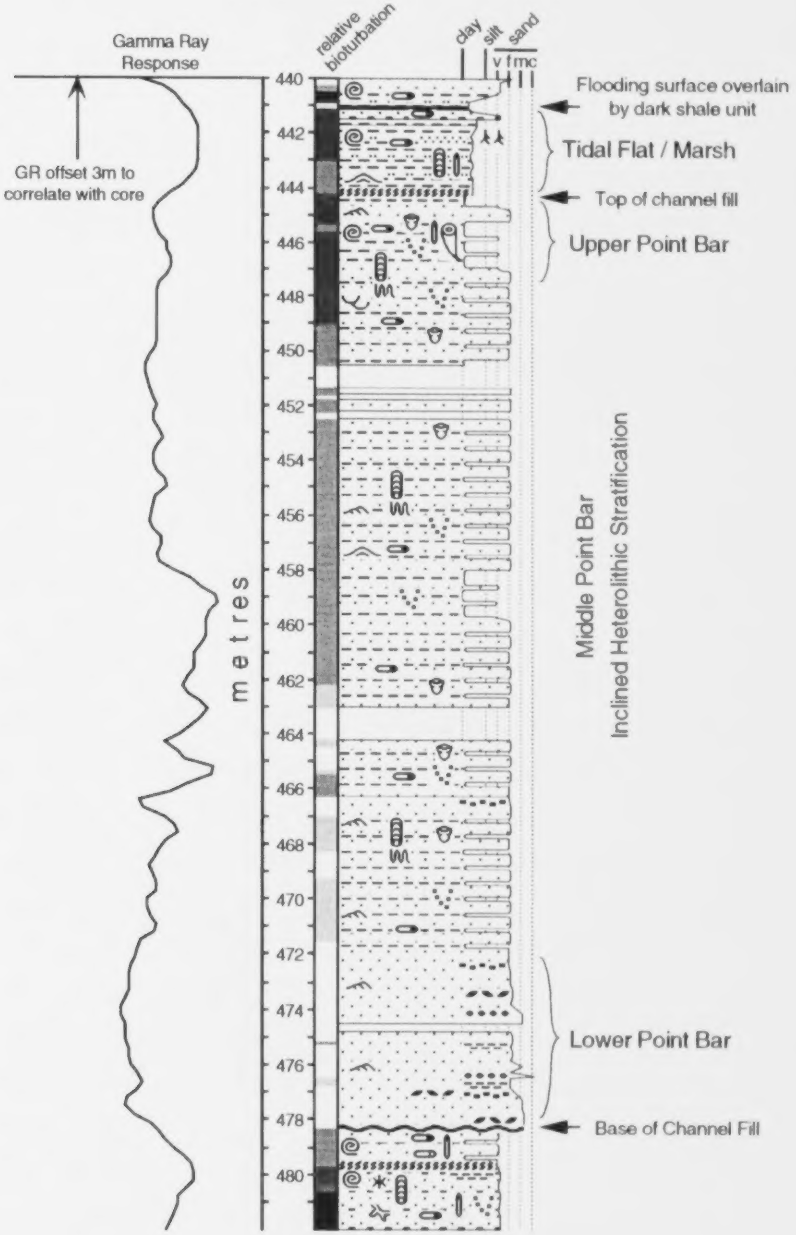
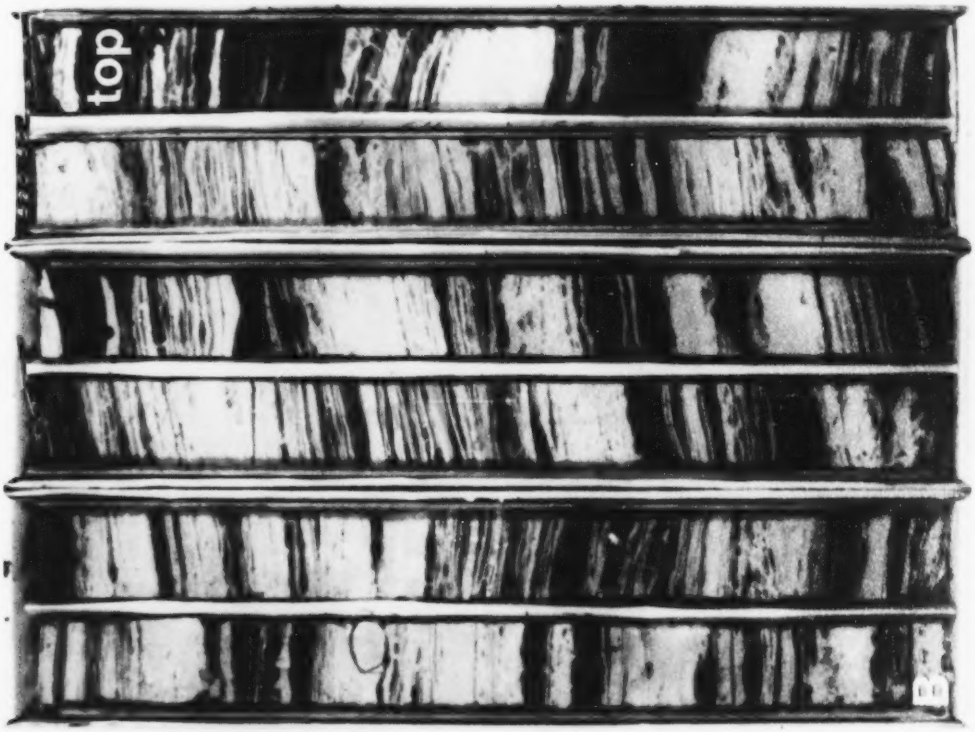

Gamma Ray Response
GR offset 3m to correlate with core
relative bioturbation
clay
silt
sand
v f m c
metres
440
442
444
446
448
450
452
454
456
458
460
462
464
466
468
470
472
474
476
478
480
Flooding surface overlain by dark shale unit
Tidal Flat / Marsh
Top of channel fill
Upper Point Bar
Middle Point Bar
Inclined Heterolithic Stratification
Lower Point Bar
Base of Channel Fill

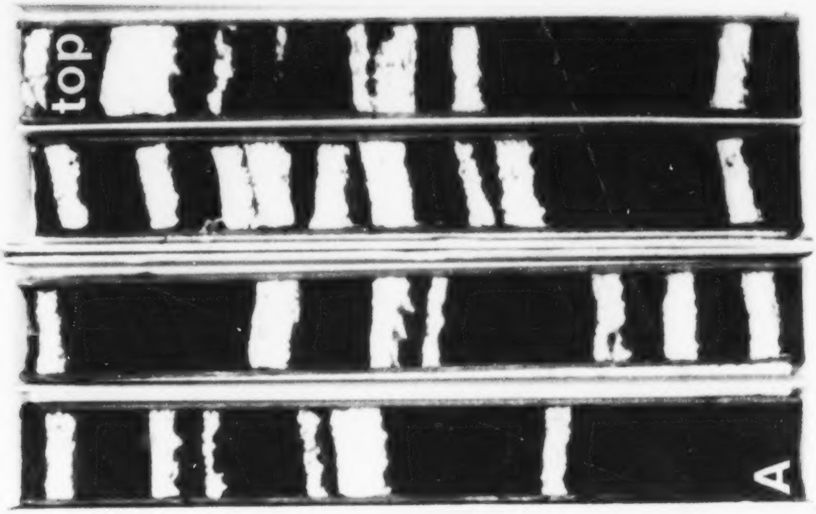
Figure III-3. Interpretive strip log for the well 10-29-73-5W4. See figure III-11 for legend.

Figure III-4.

A. Inclined heterolithic stratification from the well 10-29-73-5W4. Interval is 460.0 to 463.0 m. Note sharp contacts and burrows at the top, and penetrating into, the sand beds. Mud is light, and the sand is black with bitumen stain.

B. Mud-dominated inclined heterolithic stratification from the well 10-2-73-7W4. Interval is 520.5 to 525.0 m. Mud is light, and the sand is black with bitumen stain. Sand is restricted predominantly to flaser and lenticular beds.


top
B


top
A

away and are not preserved) and the sand beds merge into the cross-bedded basal sand. Overall the sand beds become thinner towards the top and the entire succession thus becomes generally shalier upwards.

This theme is repeated in many cores from the subsurface of the Athabasca Deposit, but the relative proportions of sand to mud, and therefore the thickness of the sand mud couplets, may vary considerably. The Pex Phillips AEC Wiau well at 10-2-73-7W4 contains a 23 m channel fill consisting of mud-dominated IHS (Fig. III-5). The bedding is inclined at a maximum apparent angle of 15°. The sands are typically developed as thin laminae, lenses and starved ripples, rarely greater than 3 cm in thickness (Fig. III-4b). The base of the channel is a fine-grained sand 0.8 m thick. Physical structures are masked by bitumen stain. In contrast, in the Gulf Resdeln well at 7-16-83-7W4, sand dominates the heterolithic bedding (Fig. III-6). In this case the base of the sand beds is strongly erosive into the mud of the underlying couplet, as demonstrated by the truncation of biogenic structures in the muds (Fig. III-7b). Evidently many of the mud beds have been totally destroyed by scouring, producing a relatively clean point bar sand, and an excellent reservoir (Fig. III-7a).

INCLINED HETEROLITHIC STRATIFICATION (IHS)

Parallel to sub-parallel inclined strata previously known as "epsilon cross-stratification" (Allen, 1963) or "longitudinal cross-bedding" (Reineck and Singh, 1975) has recently been redefined and classified by Thomas *et al.*, (1987) as "Inclined Heterolithic Stratification" (IHS). Thick sets of IHS have been recognised in many examples of modern and ancient strata (Oomkins and Terwindt, 1960; Horne *et al.*, 1978; Puigdefabregas and van Vliet, 1978; de Mowbray, 1983; Flach and Mossop 1983; MacEachern, 1989; as well as numerous others). IHS develops as lateral accretion deposits, and is generally interpreted as a migrating point bar (Howard *et al.*, 1975; Thomas *et al.*, 1987; Rahmani, 1988; Wood, 1989). Many of the modern and ancient examples of IHS invoke a tidal influence on a fluvial or estuarine system to provide the fluctuating energy regime required to produce the heterogeneous bedding, which typically consists of repetitive sets of mud/sand couplets on a scale of centimetres to decimetres (Thomas *et al.*, 1987). There are examples of purely

Pex Phillips AEC Wiau 10-2-73-7W4

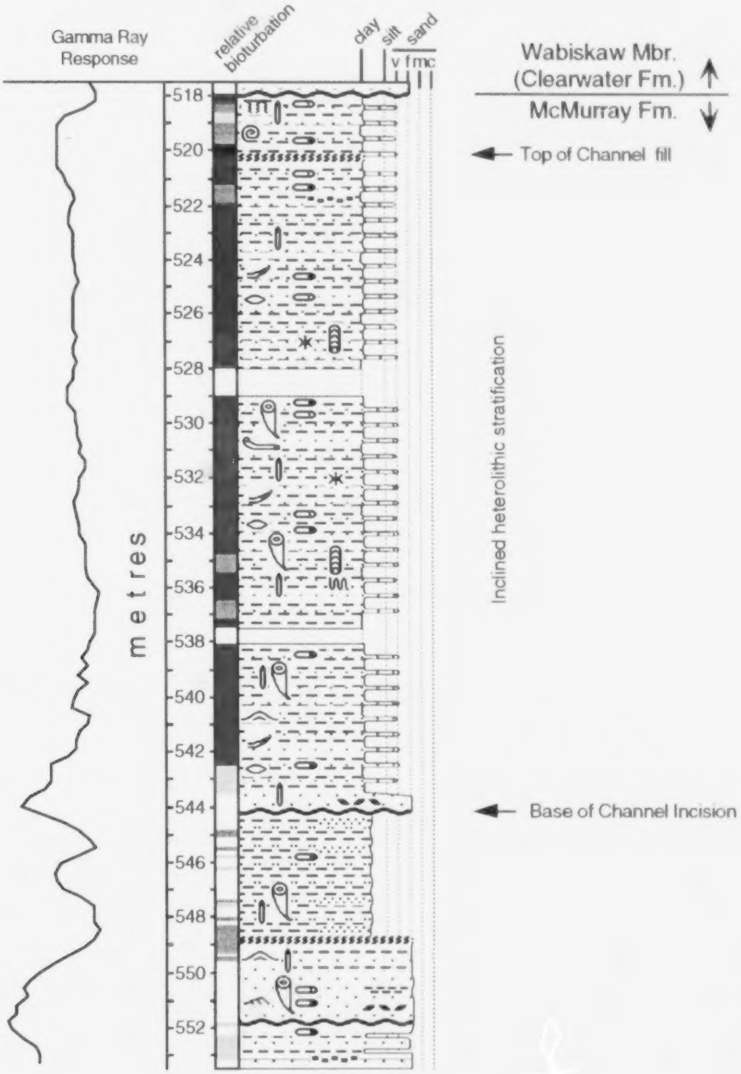

Gamma Ray Response
relative bioturbation
clay
silt
sand
v f m c
Wabiskaw Mbr. (Clearwater Fm.)
McMurray Fm.
Top of Channel fill
Inclined heterolithic stratification
Base of Channel Incision
metres
518
520
522
524
526
528
530
532
534
536
538
540
542
544
546
548
550
552

Figure III-5. Interpretive strip log for the well 10-2-73-7W4. See figure III-11 for legend.

Gulf Resdeln 7-16-83-7W4

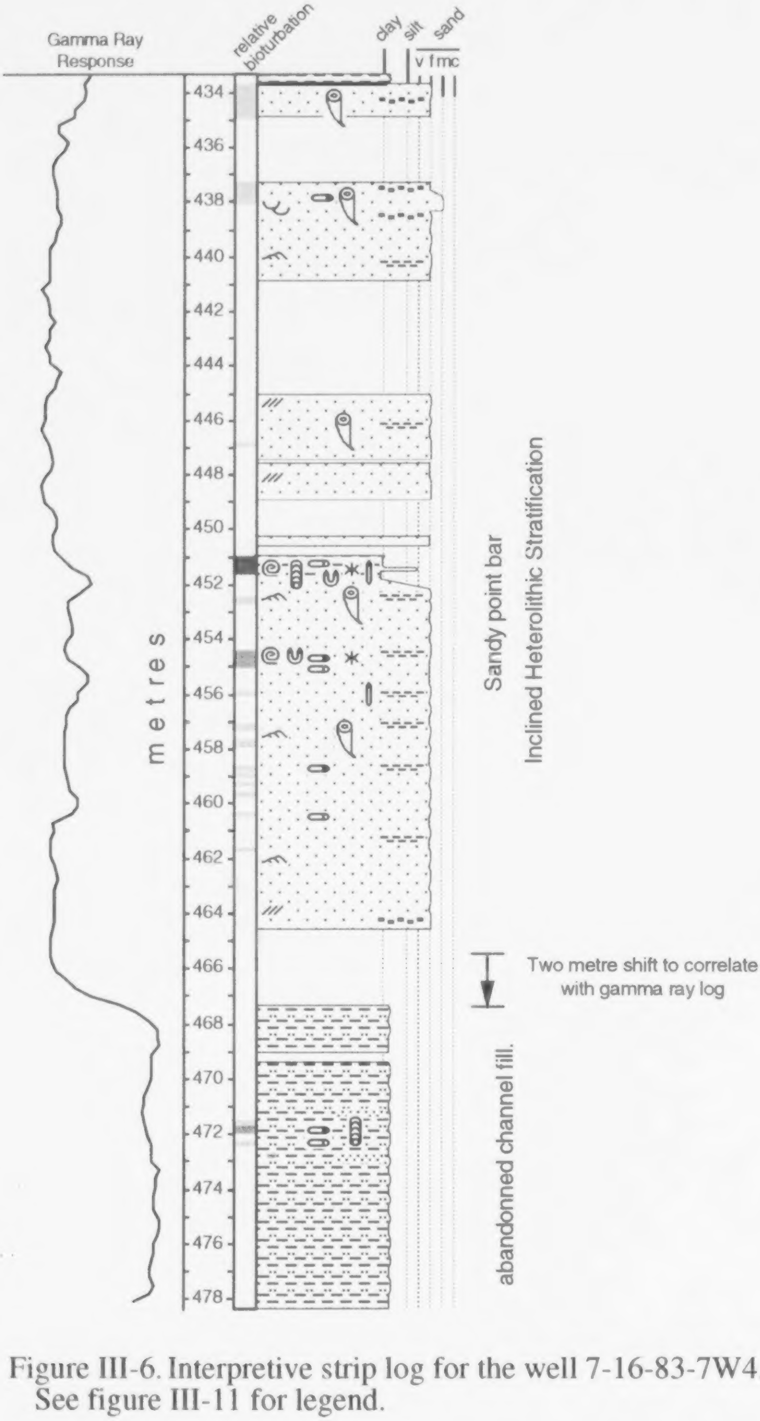
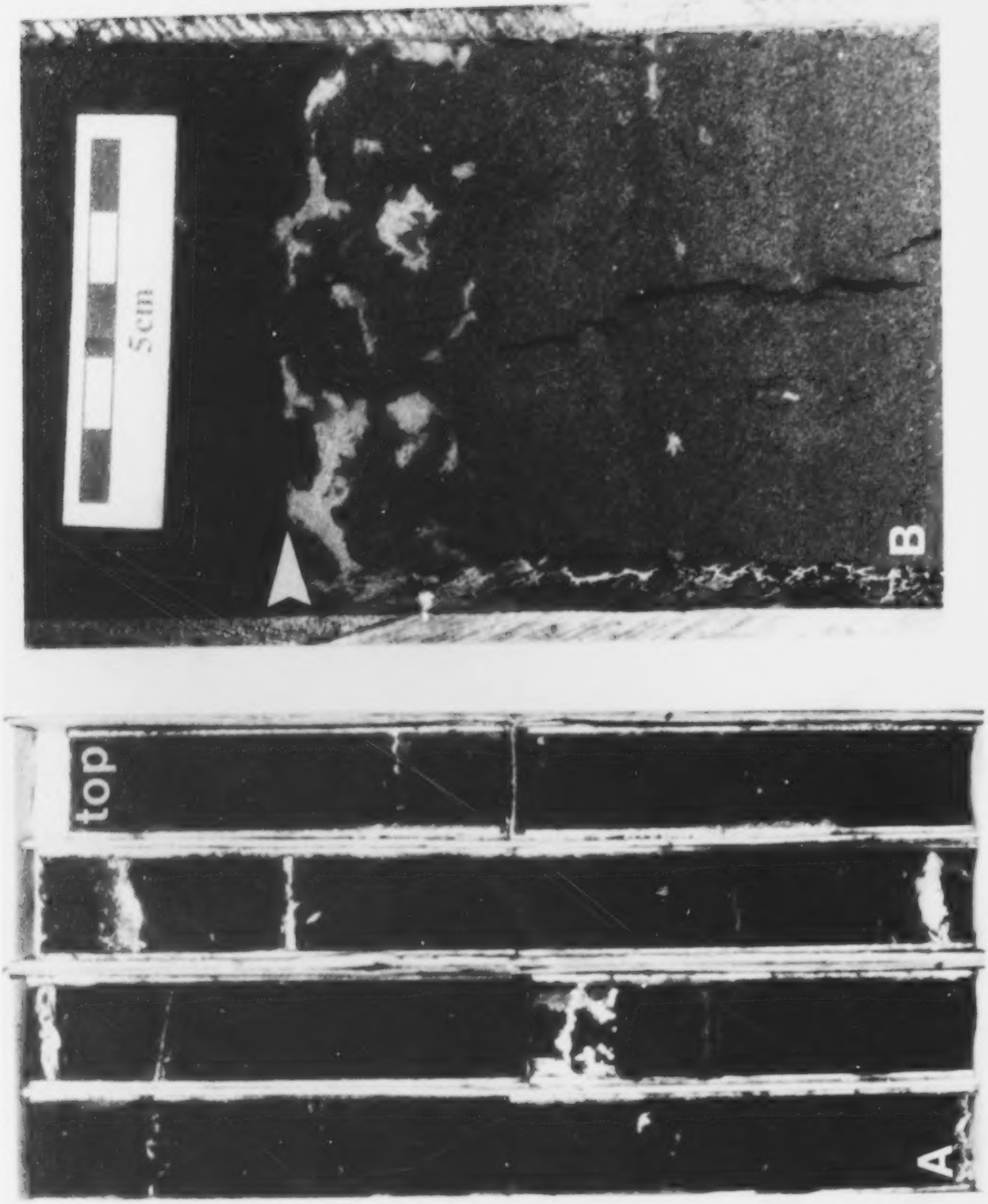

Gamma Ray Response
relative bioturbation
clay
silt
sand
v f m c
metres
434
436
438
440
442
444
446
448
450
452
454
456
458
460
462
464
466
468
470
472
474
476
478
Sandy point bar
Inclined Heterolithic Stratification
Two metre shift to correlate with gamma ray log
abandonned channel fill.

Figure III-6. Interpretive strip log for the well 7-16-83-7W4. See figure III-11 for legend.

Figure III-7.

A. Sand-dominated inclined heterolithic stratification from the well 7–16–83–7W4. Interval is 456.25 to 459.25 m. Mud is light and the sand is black with bitumen stain.

B. Scour surface at 454.5 m in 7-16-83-7W4. Arrow points to truncated *Asterosoma* burrow. Note difference in grain size above and below the scour.


5cm
B
top
A

fluvial settings that produce IHS (Jackson, 1978, 1981; Thomas *et al.*, 1987). These systems have seasonal flood cycles producing fluctuating discharge that is probably a factor in the development of the mud drapes, although the full mechanism that produces IHS in a fluvial environment is not yet completely understood.

By far the large majority of studied examples of IHS are observed in what is interpreted as migrating point bars under the influence of tidal effects, whether in a brackish lower estuary, or in the fluvial fresh water reaches of the upper estuary where tides still have an effect on the flow regime (Thomas *et al.*, 1987; Smith, 1988).

ESTUARIES - PHYSICAL CHARACTERISTICS

The dominant preserved feature of an estuary is likely to be the remnants of laterally accreting point bars as well as other channel-form deposits (Howard *et al.*, 1975; Frey and Howard, 1986). In this respect estuaries are similar to ancient meandering fluvial systems. Estuaries, however, especially those with significant fresh water discharge such as drowned river valleys, have two key characteristics that influence and complicate the sedimentation pattern.

Salt Wedge

Of key importance is the existence of a density controlled, salt water wedge that can migrate upstream and downstream along the floor of an estuary. The position of the salt wedge is largely controlled by the spring - neap tidal cycle, the rate of fluvial discharge, and major storms that can produce tidal surges up the estuary. The mixing of salt and fresh waters in an estuary is of prime importance, especially for its effect on circulation patterns, on the accumulation and flocculation of clays, and for its effect on the faunal populations inhabiting the estuarine environment. When the volume of fluvial discharge dominates the tidal volume, such as during fluvial flood cycles or during neap tides, the salt wedge will be stratified and will be displaced seaward. When fluvial discharge balances the tidal volume and especially during spring tides when the tidal amplitude fluctuates the most, fresh and salt waters become more mixed, and the salt water wedge becomes more dispersed and is displaced landward (Nichols, 1977; Allen *et al.*, 1988).

Turbidity Maximum

As a consequence of the vertical circulation patterns that are established in an estuary due to the landward flow of tidal marine waters and the seaward flow of fresh fluvial waters, a phenomena known as the Turbidity Maximum has been recognised in most modern estuaries (Haringvliet *et al.* 1960; Postma, 1967; Schubel, 1969; Allen *et al.*, 1972; Dörjes and Howard, 1975; Jouanneau and Latouche, 1981). The turbidity maximum is a zone of fluid mud accumulation associated with high flocculation rates (Kranck, 1981) and is characterised by turbidity and suspended sediment concentrations greater than that found upstream towards the fluvial system of the upper estuary, or downstream towards the lower estuary (Schubel, 1969). See Kranck (1981) and Dyer (1986) for a discussion of the development of turbidity maxima in estuarine settings. Just as the salt wedge migrates with fluvial discharge and tidal cycle, so does the turbidity maximum zone (Allen *et al.*, 1972). In fact, if the ratio of fluvial discharge to tidal volume is great enough, the turbidity maximum may be seaward of the mouth of the estuary on the open shelf, as in the case of the Amazon River (Gibbs, 1972). Typically though, a broadly tripartite facies relationship is established in an estuary, i.e.: fluvially sourced sand in the upper estuary, muddy sediments in the turbidity maximum, and sand sourced from seaward in the lower estuary (Rahmani, 1988).

The dominant sediment type accumulating as lateral accretion deposits on any migrating point bar in an estuary therefore depends on several factors: 1) proximity to the turbidity maximum; 2) the local source sediment type; 3) morphology of the point bar itself (de Mowbray , 1983; Wood, 1989); and 4) whether or not current energies are sufficient to cause resuspension of fine-grained sediments.

ICHNOLOGY OF THE ATHABASCA ESTUARINE CHANNELS

Brackish Water Environment

The ichnology of brackish water environments has been discussed in several recent studies (see Dörjes and Howard, 1975; Wightman *et al.*, 1987; Beynon *et al.*, 1988; Pemberton and Wightman, 1992), and is reviewed here only briefly. Brackish water ichnofaunal populations exhibit several characteristics typical of a stressed environment: 1) low diversity of ichnotaxa regardless of the abundance of individuals, which may be high; 2) presence of an impoverished marine assemblage of ichnofauna rather than a mixed freshwater/marine assemblage; 3) presence of elements of both the *Cruziana* and *Skolithos* ichnofacies; 4) a bias towards morphologically simple structures reflecting simple feeding strategies; 5) dominance of infaunal forms over epifaunal forms; and 6) diminished size relative to fully marine counterparts.

Brackish water ichnofauna may also reflect opportunistic or "r-selected" strategies. Organisms that employ opportunistic strategy are associated with transient, stressed, physically controlled environments (Levinton, 1970, Grassle and Grassle, 1974). Estuaries, particularly brackish riverine estuaries, are prime examples of such stressed environments. Opportunistic colonisation of a substrate thus represents an ephemeral population that grows quickly, flourishes for a short period of time, but then becomes displaced by a more stable equilibrium population of organisms (Pemberton and Frey 1984). Opportunistic strategy typically demands rapid colonisation, rapid growth and reproduction, and short life cycles, which typically dictate a small body size (Levinton, 1970).

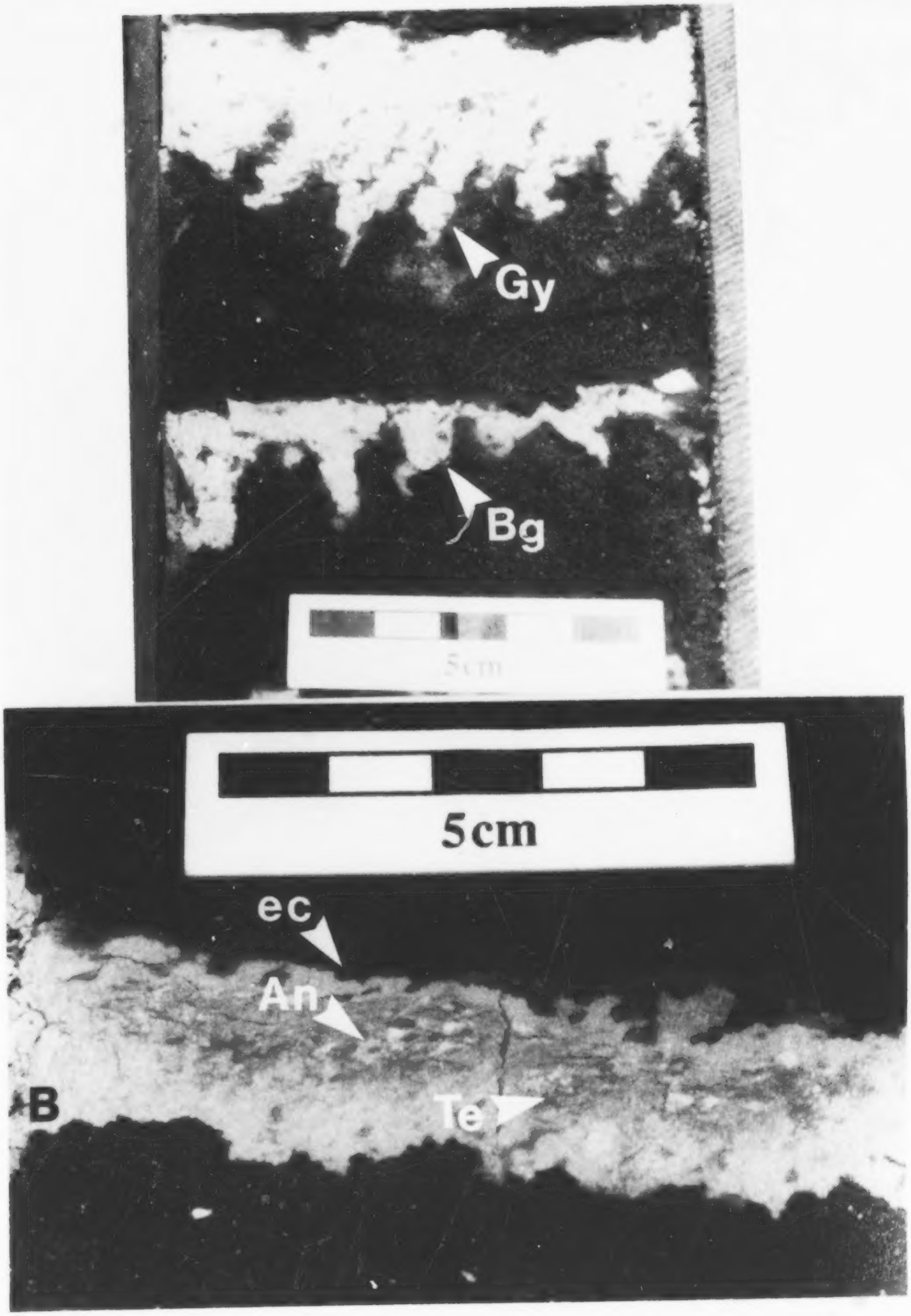
Ichnofossil Assemblage and Interpretation: 10-29-73-5W4

Several different assemblages of ichnofauna are observed in the subsurface Athabasca IHS point bars. In the 10-29-73-5W4 well, the sands lack internal burrowing. However the upper surface of the sand bed of each sand-mud couplet contains abundant specimens of the ichnogenera *Gyrolithes*, (Fig. III-8a) an ichnofossil with a spiral burrow morphology (Gernant, 1972; Powell, 1977). Plug-shaped burrows identified as *Bergaueria* (Fig. III-8a) are also associated with, but are much less abundant than *Gyrolithes*. *Bergaueria* is thought to represent the dwelling burrows of sea anemones (Alpert and Moore, 1975). This simple, almost monospecific ichnofossil suite represents the dwelling burrows of organisms that colonised the sandy substrate of the point bar following deposition of the sand component of the couplet. Both ichnofossil forms are invariably filled with mud from the

Figure III-8.

A. Ichnofossils at top of sand beds at 447.0 m in 10-29-73-5W4. The presence of *Gyrolithes* (Gy) and *Bergaueria* (Bg) at these horizons suggest conditions that supported an opportunistic population.

B. Ichnofossils in mud beds at 450.0 m in 10-29-73-5W4. *Anconichnus* (An), *Teichichnus* (Te) and epichnial casts (ec) represent the resident, equilibrium population.


Gy
Bg
5cm
5cm
ec
An
B
Te

overlying mud bed. In all cases this assemblage is observed exclusively at the interface between the sand and mud beds, and evidently the environmental conditions immediately following deposition of the sand were conducive then and only then for the colonisation of the substrate by fauna exhibiting such burrowing behaviour.

The silty mud beds of the IHS couplets directly overlying the sand are extensively burrowed. Individual traces are difficult to discern, and the bioturbation generally takes the form of disruption of primary bedding in the mud. In other studies of IHS, silty and sandy laminae have been observed in the mud units and interpreted as the diurnal tidal signature of the strata (Thomas *et al.*, 1987). In the McMurray mud beds no internal bedding remains, although reworked 'pods' of silt and fine sand may represent the remnants of such laminae. Individual ichnofossils that can be recognised in the mud include the ichnogenera *Planolites*, *Teichichnus* and *Helminthopsis*/?*Anconichnus*, representing the behaviour of deposit feeders (Fig. III-8b). Sand-filled epichnial casts on the surface of the mud beds most likely represent trails of epibenthic foragers (Fig. III-8b).

The cyclic nature of these sand - mud units and their characteristic ichnofossil assemblages conform well with what is known about the physical characteristics of an estuary. The mud beds reflect the normal brackish conditions in the estuary; the point bars slowly accumulate mud drapes over a relatively long period due its position within the turbidity maximum, seaward of the head of the salt wedge. The muddy substrate and low energy conditions support elements of the *Cruziana* ichnofacies, influenced by the variable salinity conditions imposed by the spring - neap tidal cycles. During periods of high fluvial discharge, which may be a seasonal flooding phenomenon or a random, intense, storm event , the salt wedge becomes stratified and is displaced downstream, freshening the sub-aqueous environment in the vicinity of the point bar. Accompanying this is an influx of sand entrained in the flood waters, which accumulates rapidly over only a few days. The rapid deposition and the presence of turbid fresh water precludes the colonisation of the new coarser substrate until net velocities and sediment transport return to normal rates, which may take several weeks (Nichols, 1977). The surface of the sandy substrate can then become the site of an opportunistic colonisation chiefly by the *Gyrolithes* trace-making organism. This colonisation would necessarily be short-lived because once the turbidity maximum returns to its normal physiographic position and mud once more begins to accumulate, the substrate is no longer conducive to the type of behaviour exhibited by the opportunistic fauna; they are literally 'smothered', and their burrows filled with mud. The faunal population then returns to its equilibrium state: endobenthic deposit feeders and epibenthic foragers. In many ways, the equilibrium ichnofauna may also be considered opportunistic or r-selected, especially if fluvial flood events are regular seasonal occurrences. Survival in such conditions would require rapid colonisation, rapid reproduction and rapid grow over a period of less than one year.

Ichnofossil Assemblage and Interpretation: 7-16-83-7W4

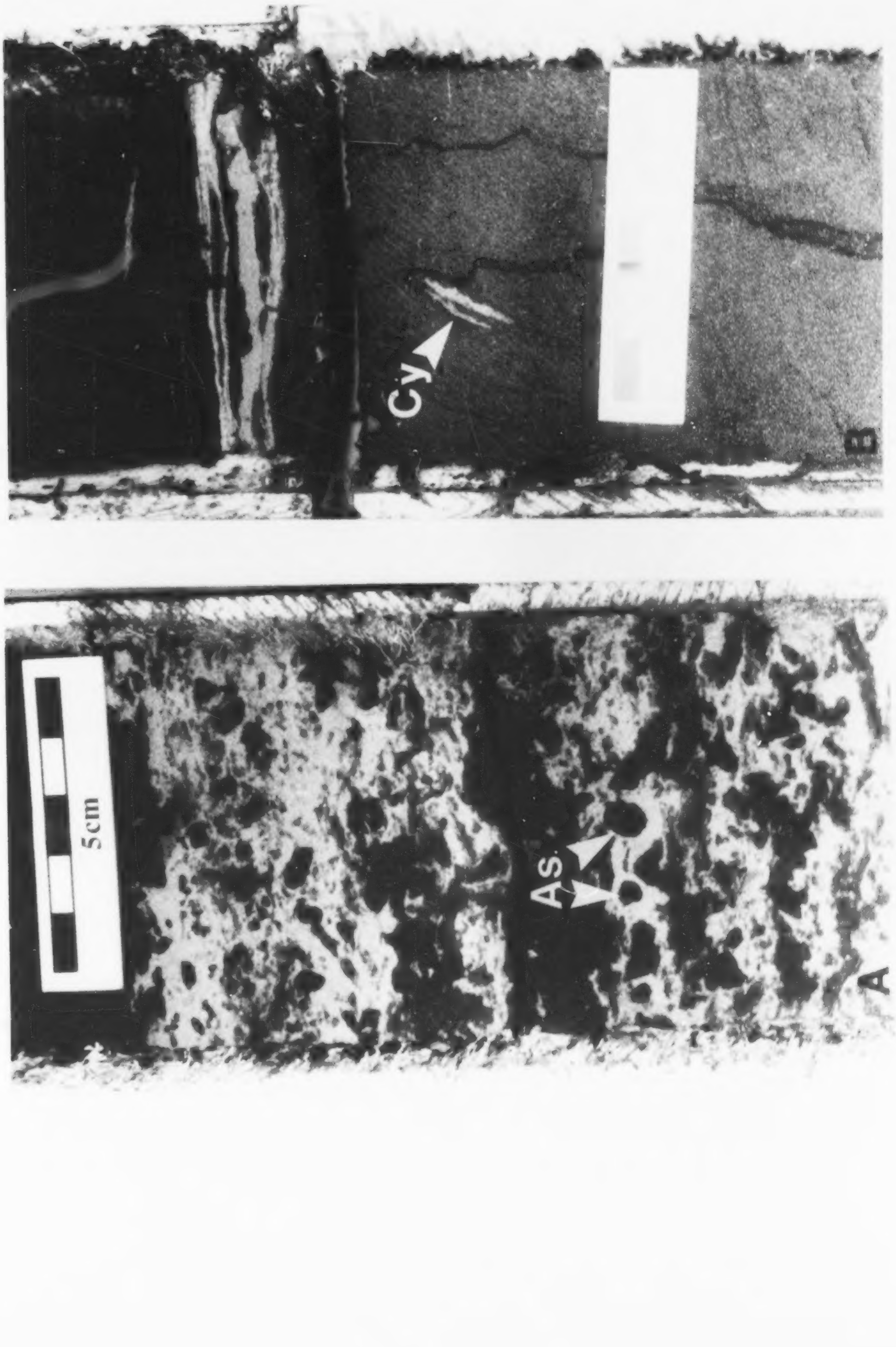
The physiographic position of the sandy estuarine point bar penetrated in the well at 7-16-83-7W4 may have been seaward of the turbidity maximum. In this position the point bar is subject to little mud deposition except during periods of high fluvial discharge, which would displace the turbidity maximum downstream. As described above, most of the mud beds are poorly preserved, and it can be inferred that many were totally eroded by subsequent events. Where preserved, the muds appear to have supported an abundant, stable, faunal population. The ichnogenera *Asterosoma, Arenicolites, Palaeophycus, Planolites* and *Skolithos* have been identified (Fig. III-9a), representing both deposit-feeding and dwelling structures. The sands may be locally sourced from erosion of the cutbank, or brought in from the seaward direction during major storm surges. Therefore, the sand beds may also be the result of episodic events, the equilibrium state on the point bar being reworking of sand by diurnal tidal currents. In contrast to the 10-29-73-5W4 well, the sands do contain an internal monospecific ichnofauna consisting of rare, small *Cylindrichnus* shafts (Fig. III-9b). This suggests that the sand accumulated relatively slowly, under brackish conditions.

The 7-16-83-7W4 well also penetrates a 12 m thick, laminated, but otherwise structureless, mud that is almost totally barren of ichnofossils (Fig. III-10a). Its upper and lower contacts are missing or not recovered, but this

Figure III-9.

A. Ichnofossils in a muddy bed at 450.0 m within the sand-dominated IHS in 7-16-83-7W4 (As): *Asterosoma.*

B. A single *Cylindrichnus* (Cy) shaft at 459.6 m in a sand-dominated IHS interval in 7-16-83-7W4.


B
Cy
A
As
5cm

interval is interpreted to represent an estuarine channel abandonment mud plug. The only bioturbation observed in this mud interval is associated with a few minor laminae of silt or sand, and consists of *Planolites*, and rare *Teichichnus* and *Palaeophycus* (Fig. III-10b). Following avulsion, an abandoned estuarine channel meander would slowly become plugged in a fashion similar to an abandoned fluvial meander. The only sediment influx into the resulting pond would be due to turbid, overbank, freshwater flow during flood events. As discussed above, flood events in an estuary result from large fluvial discharge, which is accompanied by freshening of the estuary, especially near the surface. The abandoned channel thus periodically becomes flooded with fresh water and suspended sediment, which slowly accumulates over time creating the preserved plug. The rare bioturbation that is observed may be due to organisms washed in along with suspended silt and very fine sand during extreme tidal storm surges, which overwhelm the fresh water lens in the estuary.

Ichnofossil Assemblage and Interpretation: 10-2-73-7W4

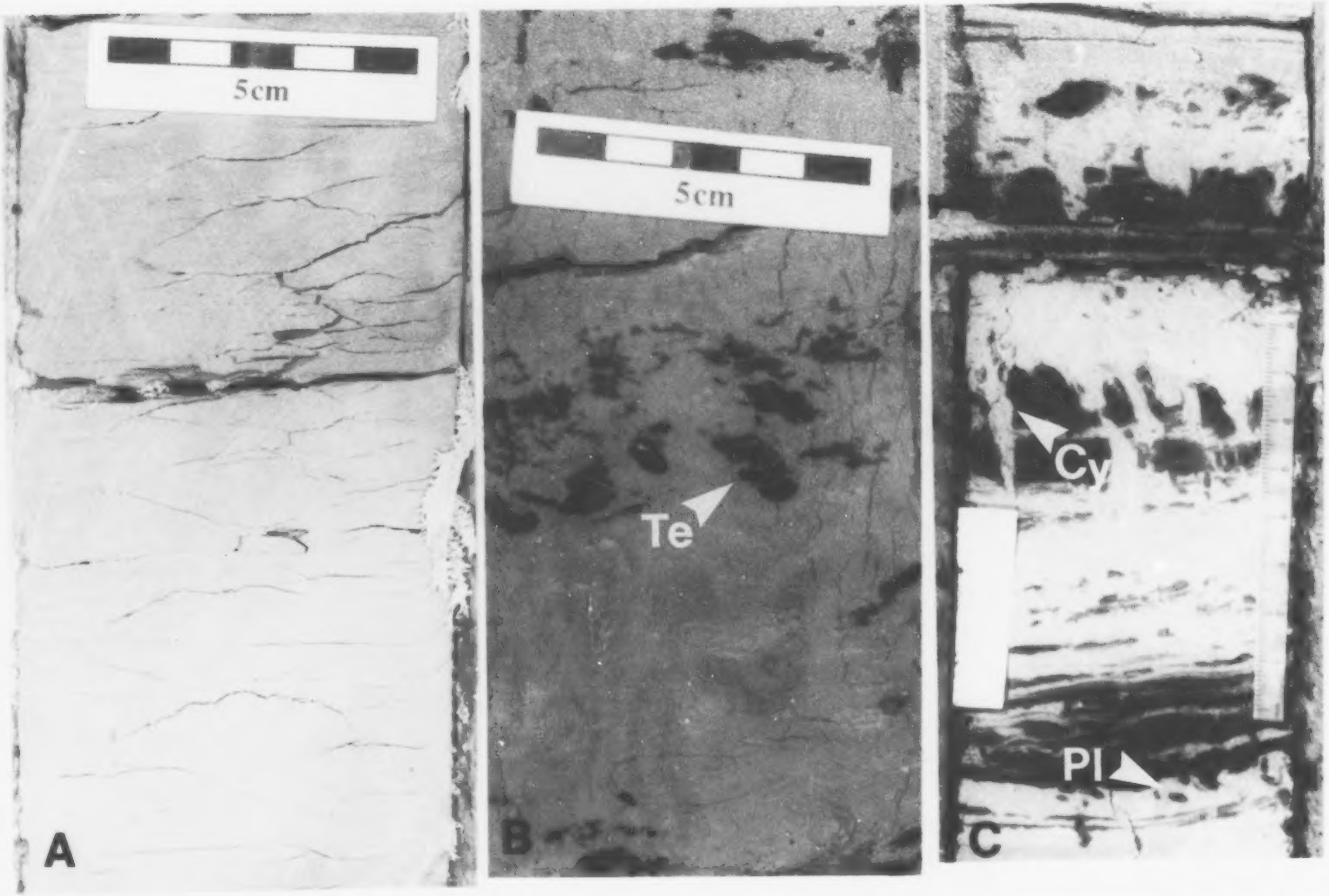
The well at 10-2-73-7W4, which penetrates a 24 m thick, mud-dominated, estuarine point bar deposit, composed of IHS, is interpreted to have accumulated largely within the turbidity maximum of an estuarine system. The mud beds may or may not be bioturbated. The bioturbated muds represent the equilibrium state on the point bar, which aggraded predominantly by settling of fines out of suspension aided by flocculation of clays. These muds are dominated by burrows of the ichnogenera *Cylindrichnus*, *Planolites* and *Skolithos* (Fig. III-10c). Sand or mud-filled epichnial casts may be observed at bedding interfaces, and represent the trails of epibenthic foragers. *Teichichnus*, *Palaeophycus*, *Asterosoma* and *Helminthopsis*/?*Anconichnus* are also present. These forms are considered the resident equilibrium population, and represent a mixed *Skolithos*-*Cruziana* ichnofacies. The ichnofaunal population is therefore low in diversity, although individuals may be abundant and it represents an impoverished marine assemblage. All forms are generally small in size, and the assemblage is dominated by infaunal forms. These features are all characteristics of brackish conditions. The mud beds that are barren of

Figure III-10.

A. Laminated mud barren of ichnofossils at 465.75 m in 7-16-83-7W4. The entire interval is over 10 m thick, and is interpreted to be a mud plug in an abandoned channel.

B. A rare bioturbated zone in an otherwise barren mud plug from 470.0 m in 7–16–83–7W4. Te: *Teichichnus.*

C. Ichnofossils from a mud-dominated IHS interval at 433.0 m in 10-2-73-7W4. Cy: *Cylindrichnus.* Pl: Planolites.


5cm
5cm
Te
Cy
Pl
A
B
C

ichnofossils are up to 15 cm thick and have a sharp contact at the base. These barren muds probably represent periods of rapid deposition of flocculated clays settling from suspension accompanied by an influx of fresh water (Ranger and Pemberton, 1988), conditions indicative of high fluvial discharge associated with flood conditions. The thin sand laminae are generally lenticular to flaser bedded, and such features are usually interpreted as indicating deposition under tidal influence (Frey and Howard, 1986), although they may represent the effects of spring tide surges rather than a strictly diurnal cycle. The thicker sand beds may be the result of extreme high tides such as that created by storm surges, or alternatively may represent extreme discharge conditions during the strongest fluvial flood cycles, when the turbidity maximum is displaced far downstream.

CONCLUSIONS

Estuarine channel point bars from the McMurray Formation of the subsurface Athabasca Oil Sands can be recognised by a number of characteristics: 1) They are typically thick facies intervals that represent single genetic units and which differ from the 'background' highstand systems tract of stacked, prograding, brackish shoreface parasequences. 2) They commonly display IHS, consisting of mud - sand couplets, which vary in thickness from decimetres to laminae and may be sand-dominated or mud-dominated. 3) The effects of periodic events that are responsible for high rates of deposition, and salinity and turbidity stress are clearly evident in the ichnofaunal assemblages. These consist of intervals that are barren of ichnofossils and bedding interfaces that supported an opportunistic population. 4) The ichnofaunal suites that represent the stable, equilibrium population display many of the characteristics of brackish water assemblages.

Mud intervals several metres, or tens of metres, thick that are barren of ichnofossils are interpreted as fill in abandoned estuarine channels, which periodically were flooded with turbid fresh water due to overbank flooding during periods of high fluvial discharge.

Whether the point bar cores are sand- or mud-dominated probably depends on their physiographic position relative to the turbidity maximum in the estuary. However other factors may play a role, such as the local sediment source, morphology of the point bar, and relative strength of currents. From a reservoir point of view, the sand-dominated point bars are clearly to be preferred, and therefore delineating the turbidity maximum zone in an ancient estuarine complex can be critical to exploration. Even within the sand-dominated point bars, the presence of cyclic mud beds may lower the quality of the reservoir. Based on analogues in outcrop, the muds can be expected to be relatively continuous from the top of the point bar almost down to the toe, thus affecting both lateral and vertical permeability.

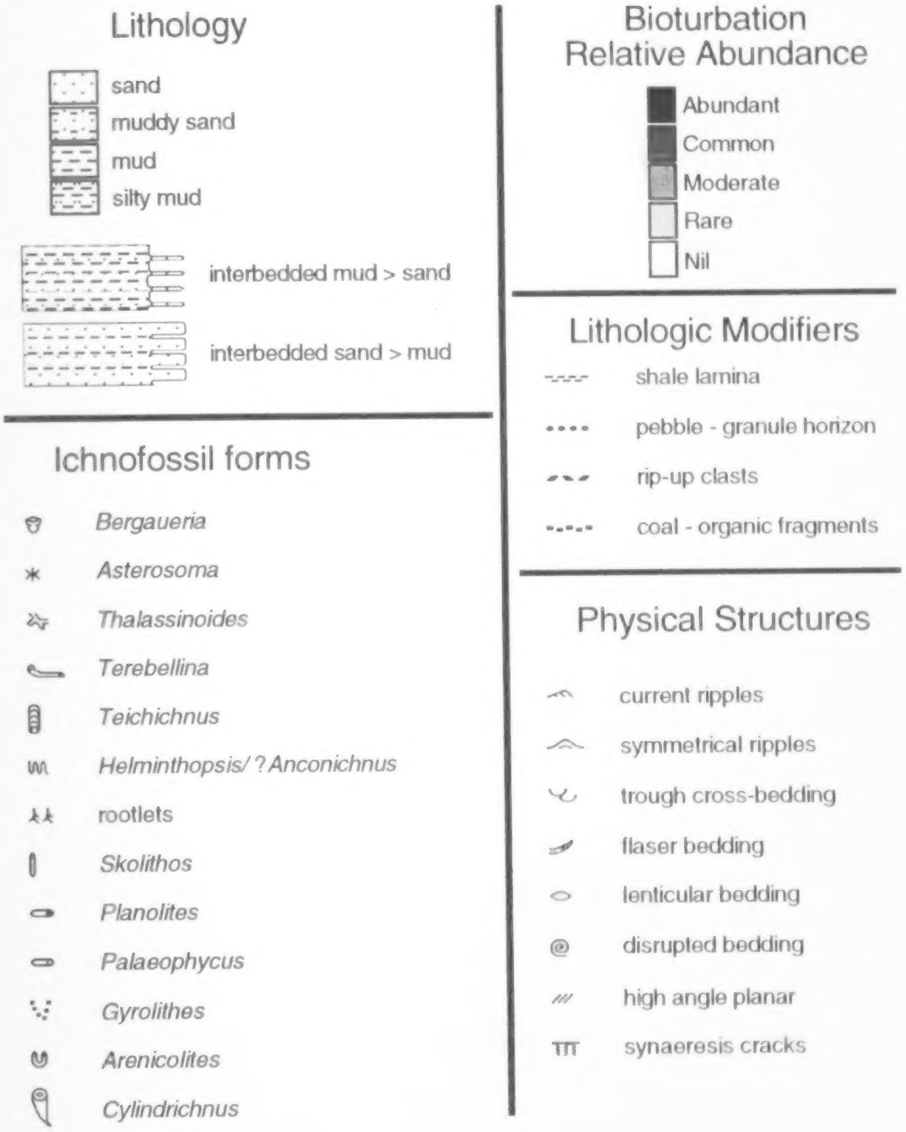

Lithology
sand
muddy sand
mud
silty mud
interbedded mud > sand
interbedded sand > mud
Bioturbation Relative Abundance
Abundant
Common
Moderate
Rare
Nil
Lithologic Modifiers
shale lamina
pebble - granule horizon
rip-up clasts
coal - organic fragments
Ichnofossil forms
Bergaueria
Asterosoma
Thalassinoides
Terebellina
Teichichnus
Helminthopsis/ ? Anconichnus
rootlets
Skolithos
Planolites
Palaeophycus
Gyrolithes
Arenicolites
Cylindrichnus
Physical Structures
current ripples
symmetrical ripples
trough cross-bedding
flaser bedding
lenticular bedding
disrupted bedding
high angle planar
synaeresis cracks

Figure III-11. Legend for interpretive strip logs.

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CHAPTER IV

MULTIVARIATE ANALYSIS OF ICHNOFOSSIL ASSOCIATIONS IN THE SUBSURFACE BLUESKY FORMATION (ALBIAN, ALBERTA, CANADA)[1]

INTRODUCTION

The quantitative analysis of ichnofossil data is a field of growing interest, but with relatively few published studies (e.g. Shroud and Levin, 1976; Miller, 1977; Marintsch and Finles, 1978; Kitchell, 1979; Pemberton and Frey, 1984b; Bjerstedt, 1988; Demathieu and Wright, 1988; and Moratalla *et. al.*, 1988). Most of these have dealt with spatial distribution on the modern sea floor (e.g. Kitchell and Clark, 1979; Ekdale *et al.*, 1984), or from discrete bedding planes of an outcrop that are assumed to have supported a contemporaneous community of organisms (e.g. Pemberton and Frey, 1984b; Bjerstedt, 1988). As such, they have focused on ecological relationships inferred from ichnological evidence for a single point in time.

Ichnological associations from diamond drill cores cannot be used to infer spatial relationships in a strict temporal sense because of the limited sample size afforded by a single bedding plane in a core and the relatively great distance between sample points. Even where cored wells are closely spaced, individual bedding planes cannot normally be correlated from well to well with sufficient confidence.

On the other hand, core lends itself to the study of the vertical changes in ichnological associations from which one may infer the change of paleoecological conditions with time. The study of vertical change in the distribution of paleoenvironments is a key tool in the reconstruction of ancient depositional systems, and the extrapolation of vertical sequences to lateral dimensions is commonly attempted based on Walther's Law of the Correlation of Facies: "...only those facies and facies-areas can be superimposed primarily which can be observed beside each other at the present time" (Middleton, 1973).

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[1] A version of this chapter has been published. Ranger, M.J. and Pemberton, S.G. 1991. Multivariate analysis of ichnofossil associations in the subsurface Bluesky Formation (Albian, Alberta, Canada). Palaeogeography, Palaeoclimatology, Palaeoecology, v. 85, pp. 169-187.

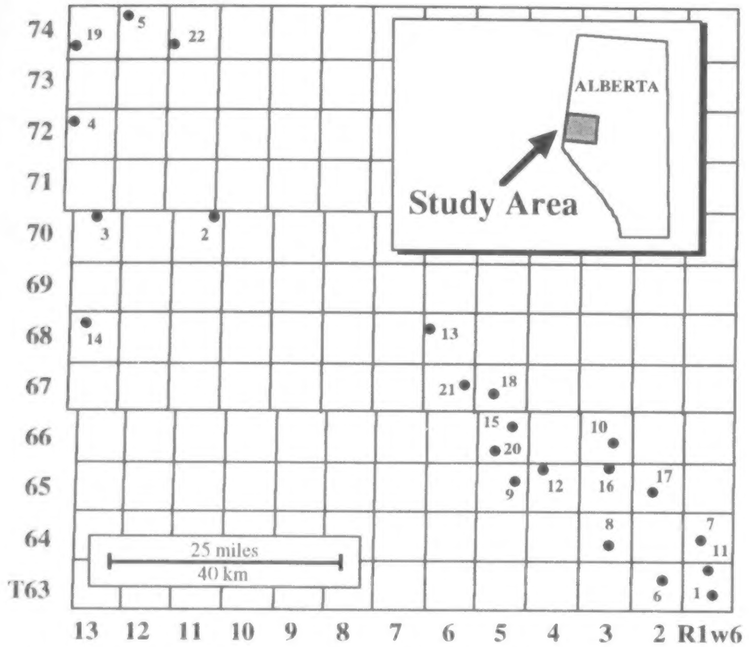
In contrast to body fossils, ichnofossils have unique value in the interpretation of paleoenvironments. Ecological evidence from body fossils is sparse and biased due to diagenetic and physical destruction. Also, the spatial occurrence of the death assemblage of the remains of an organism is usually considerably different from its living habitat. Ichnofossils on the other hand represent the manifestation of behaviour of the living organism and record its response to prevailing paleoenvironmental conditions. Ichnofossils are almost invariably found *in situ* and are commonly enhanced rather than destroyed by diagenesis.

Increasing numbers of subsurface sedimentological studies leading to paleoenvironmental interpretations are using ichnological associations as key evidence (e.g. Tillman *et al.*, 1981; Reinson *et al.* 1983; Krause and Nelsen, 1984; Bergman and Walker, 1986; Siemers and Ristow, 1986; Thompson *et al.* 1986; Wightman, *et al*, 1987; Beynon *et al.* 1988; Ranger and Pemberton, 1988; and Vossler and Pemberton, 1988). In these studies ichnological evidence is used in a qualitative manner as part of a facies description, but there appear to be no published studies in which ichnofossil associations in core have been examined using quantitative techniques.

The present study establishes the vertical development and lateral persistence of paleoenvironments through the Bluesky Formation of northwestern Alberta. An interpretation is based on the statistical treatment of the occurrence, association and diversity of ichnotaxa from cored intervals of 22 wells (Fig. IV-1) that penetrate the Bluesky Formation. Q-mode and R-mode cluster analyses established discrete ichnofossil associations and discriminated several ichnocoenoses into which each facies interval could be classified. Markov chain analysis determined a significant preferred vertical transition of the ichnocoenoses through the Bluesky Formation interval.

STRATIGRAPHIC SETTING OF THE BLUESKY FORMATION

The Bluesky Formation (Fig. IV-2) has been interpreted as the deposits of regressive pulses in an overall transgressive phase of the Lower Albian Boreal Sea (Jackson, 1984). Over most of the study area the Bluesky Formation is a coarsening upwards, marine shoreline sand, possibly


74
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5
4
3
2
R1w6
19
5
22
4
3
2
14
13
21
18
15
20
10
9
12
16
17
8
7
11
6
1
25 miles
40 km
ALBERTA
Study Area

Figure IV-1. Location map showing the distribution of the 22 cores used in the study of the Bluesky Formation.

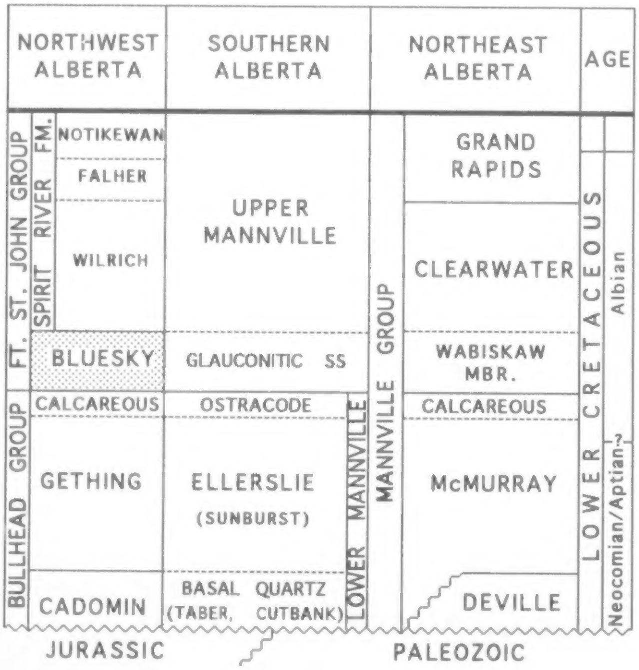
NORTHWEST ALBERTA
SOUTHERN ALBERTA
NORTHEAST ALBERTA
AGE
FT. ST. JOHN GROUP
SPIRIT RIVER FM.
NOTIKEWAN
FALHER
WILRICH
BLUESKY
BULLHEAD GROUP
CALCAREOUS
GETHING
CADOMIN
UPPER MANNVILLE
GLAUCONITIC SS
OSTRACODE
ELLERSLIE
(SUNBURST)
BASAL QUARTZ
(TABER, CUTBANK)
LOWER MANNVILLE
MANNVILLE GROUP
GRAND RAPIDS
CLEARWATER
WABISKAW MBR.
CALCAREOUS
McMURRAY
DEVILLE
LOWER CRETACEOUS
Albian
Neocomian/Aptian
?
JURASSIC
PALEOZOIC

Figure IV-2. Stratigraphic setting of the Bluesky Formation.

constituting a northward (seaward) prograding barrier bar system. The sediments are glauconitic and abundantly bioturbated (Smith *et al.*, 1984).

To the south and southwest, the Glauconitic Sandstone of the Upper Mannville is a lithostratigraphic equivalent to the Bluesky Formation, although possibly somewhat younger in age (Jackson, 1984). The Glauconitic Sandstone constitutes beach and deltaic deposits in the Primrose area (Tilley and Longstaffe, 1984), and barrier bar to offshore marine sands in the Hoadley area of south central Alberta (Chiang, 1984).

Northeast of the study area the Bluesky Formation sands are part of the reservoir system for the Peace River oil sands deposit. They are also the lithostratigraphic equivalent to the Wabiskaw Member of the Clearwater Formation of northeastern Alberta, where they form part of the reservoir system for the Athabasca Oil Sands Deposit. The Bluesky Formation at Peace River has been interpreted to represent deposition under marine conditions (Outtrim and Evans, 1977), while the Wabiskaw Member sands are believed to constitute open-marine shelf bars (Ranger *et al.*, 1988). A recent study by O'Connell (1988), incorporating the northern one-third of the present study area, recognised offshore marine, wave-dominated shoreface deposits and tidally dominated inshore deposits.

DATA

The core from 22 wells that penetrate the Bluesky Formation were described and all ichnofossils were identified. The cores had previously been subdivided into facies intervals based on physical sedimentology. Eleven ichnofossil suites had been subjectively defined based on the presence and abundance of specific ichnotaxa. This existing subjective classification into ichnofossil suites proved valuable as a control by which to judge the various classification schemes produced purely by statistical methods.

The occurrence of ichnotaxa in each facies interval was recorded on the core description logs, but the number of occurrences of each species had not been determined. Relative abundance was summarised in a description of the eleven ichnofossil suites, but only in a relative, categorical sense (i.e. rare, moderate, common, abundant). Relative abundance was therefore not considered in this study.

From a statistical standpoint, relative abundance data would be heavily biased because: 1) a core represents a very small, possibly non-representative sample size; 2) ichnofossil morphology dictates that some forms are preferentially exposed in core (e.g. horizontal burrows are more likely to be intersected than vertical burrows); 3) smaller burrows can be expected to be more abundant than larger burrows; 4) some abundant forms may occur in colonies that are heterogeneously distributed; and 5) an abundance of a specific form at one horizon in a core may simply reflect the behaviour of a single tracemaker (e.g. the radiating arms of an *Asterosoma* burrow). The statistical classification schemes were thus based solely on variables that constituted the presence or absence of particular ichnotaxa. The presence of synaeresis cracks, a definitive physical sedimentary structure, was also used in the analysis. Because these variables can only have one of two states (presence or absence), they are termed binary variables. Note that the number of different ichnotaxa in a facies interval can be used as a simple estimate of its diversity (Kitchell, 1979).

There were several short intervals of lost core, many of which had the same facies recorded above and below the lost interval, and displayed a constant geophysical log response across the interval. It was assumed that in such cases the facies persisted over the missing core interval.

From the 22 cores, 140 facies intervals had been recorded. These constitute the samples or entities in the data set. The presence or absence of 25 ichnotaxa was reduced to 18 by the exclusion of forms that occurred only very rarely. They were not considered to contribute significant information to the classification scheme. Their rare occurrence probably means that they had a low relative abundance, so that even if they were characteristic of a particular ichnofossil association, the probability of intersecting them in a core is very low. The presence or absence state of these remaining 18 structures thus constitute the variables or attributes of the entities in the data set.

METHODS

Cluster Analysis

Cluster analysis is a technique for grouping samples or entities into discrete classes based on recurrent common attributes. The first step in a cluster analysis is to calculate a matrix of similarity coefficients. Between all possible pairs of entities, a coefficient is calculated that represents their distance apart in multidimensional space (Davis, 1973). If the attributes are continuous data (rather than binary), then the set of attribute values are an entity's coordinates in this multidimensional space. For binary data however, this 'distance' coefficient is a simple function based on the presence or absence of the attributes. A multitude of similarity or dissimilarity coefficients have been proposed. In this study several of the most common coefficient equations (Hazel, 1970) were evaluated to determine which performed best. These are:

- Euclidian Distance: (B+C) / M (dissimilarity)
- Simple Matching Coefficient: (A+D) / M (similarity)
- Similarity Ratio (Jaccard Coefficient): A / (A+B+C) (similarity)
- Error Sum of Squares: (B+C) / 2M (dissimilarity)

where for each pair of entities i and k:

A = number of attributes common to both entities
B = number of attributes present in entity i but absent in entity k
C = number of attributes present in entity k but absent in entity i
D = number of attributes absent in both entities
M = A+B+C+D = the total number of attributes. (Wishart, 1987)

The next step in cluster analysis is the fusion of the two entities that have the greatest similarity into a single cluster. The similarity coefficients are then recalculated based on some transformation function that combines the similarity coefficients of the fused entities. The fusion of entities and/or clusters of entities is continued until all entities reside in a single cluster. Only four of the most common were evaluated in this study. These are:

- Single Linkage (nearest neighbour, minimum method)
- Complete Linkage (furthest neighbour, maximum method)
- Average Linkage (unweighted pair group)
- Error Sum of Squares (Ward's Method)

These functions are described in detail in Wishart (1987).

The choice of an optimum similarity coefficient function and fusion transformation function is somewhat subjective and can be based on a knowledge of the data, previous experience, or trial and error (Everitt, 1980). In this study however, there is a control classification consisting of the original subjective assignment of the facies intervals (entities) to one of 11 ichnofossil suites. To aid in the evaluation of an optimum combination of similarity coefficient and transformation function, different combinations of the two were utilised to cluster the data. Then hierarchical fusion was run until 11 clusters remained, the same number of original ichnofossil suites. The assumption was made that the optimum numerically derived classification should come closest to the subjective classification, although there would no doubt be considerable divergence due to the qualitative judgment used in a subjective classification.

Within each of these 11 numerically derived classes the frequency of occurrence of the subjectively assigned ichnofossil suite was tallied. The suite with the highest frequency was considered to be the “correct” suite represented by the numerically derived class. The fact that the same ichnofossil suite may have dominated more than one class was ignored. The "misclassified" facies intervals were then summed over the whole data set to give a "misclassification" score. The combinations of similarity coefficient and transformation function giving the lowest misclassification scores were then deemed preferable.

Although 11 clusters were used in the evaluation of clustering functions, this is not necessarily the best working number. The optimum number of clusters or classes for a particular study is often a subjective decision based on a knowledge of the data. However, there exist many different tests or “stopping rules” for aiding in the selection of a significant number of clusters in a data set (Milligan and Cooper, 1985). In this study we employ a widely-known statistical stopping rule known as the Mojena or “upper tail” rule (Mojena, 1977). This rule corresponds to a one-tail confidence test using the distribution of similarity coefficients at each stage in the hierarchy (Milligan and Cooper, 1985). As a further visual aid in determining a suitable number of clusters, the change in similarity coefficient with successive fusion cycles can be plotted on a graph. A large change in magnitude of the similarity coefficient between two clusters being fused in a particular cycle signals a relatively "forced" clustering. The immediately preceding number of clusters should then be examined for efficacy and workability.

The cluster analysis technique discussed above, which groups facies intervals together into clusters based on the presence or absence of ichnotaxa, is considered to be a Q-mode cluster analysis. The facies intervals are the entities and the ichnotaxa are the attributes. Q-mode cluster analysis therefore measures species similarities among samples. In R-mode cluster analysis the roles are reversed so that the ichnotaxa become the entities and the facies intervals become the attributes. R-mode cluster analysis thus measures species associations. Hazel (1970) described the relationship between R- and Q-mode cluster analysis more succinctly: "In Q-mode, objects (samples) are related to each other on the basis of their attributes (species). In R-mode attributes are related to each other of the basis of the objects in which they are found". In this study R-mode cluster analysis was run in order to distinguish ichnological associations, i.e. which ichnotaxa tend to occur together within the facies intervals. All of the cluster analyses were performed utilising the CLUSTAN package of programs (Wishart, 1987).

In the data set used for this study, there were several facies intervals that contained no burrowing. To prevent division by zero in the Jaccard coefficient calculation, which gives no weight to the mutual absence of an attribute, it was necessary to include another attribute, the presence of which indicates "no burrowing". Including "no burrowing" as an attribute does create some redundant data and removes one degree of freedom, because the absence of all other attributes forces the "presence" of no burrowing. Problems with its use arise in the R-mode analysis. Because hierarchical clustering ultimately fuses all entities into a single cluster, at some point the attribute of no burrowing must be fused into a trace fossil association. This is obviously an irrational situation. For these reasons, the attribute of no burrowing was included in the Q-mode analyses, but not the R-mode analyses.

Both R-mode and Q-mode clustering produces an hierarchical ordering of the entities based on their similarity. This ordering can be used to produce a two-dimensional contingency table that helps to visualise the order and associations produced by the cluster analysis (B. Jones, 1987: personal communication).

Markov Analysis

Markov analysis measures the probability of transition from one state to another in a sequence of data. A Markov property or Markov process is one in which the probability of a process being in a given state at a particular point in time may be deduced from knowledge of the immediately preceding state or states (Harbaugh and Bonham-Carter, 1970). Facies states may comprise lithofacies (e.g. Ethier, 1975; Cant and Walker, 1976; May and Jones, 1982; Johnson, 1984, among many others), biofacies, or even structural criteria (e.g. Naylor and Woodcock, 1977). Ichnological data may be expected to show the Markov property in a similar way to lithofacies. Because ichnofossils represent convergent evolutionary patterns of animal behaviour (Elders, 1975), they typically have very long ranges, and can therefore be expected to recur in the same manner that lithofacies patterns recur. Cyclic lithofacies patterns are the basis for facies models (Walker, 1979), and it seems possible that recurring ichnological associations could provide valuable models as well. Although the results of this study do not establish a general model, they do demonstrate that transitions of ichnocoenosis states can exhibit a Markov process.

In the variation of the technique most commonly used for stratigraphic studies, the frequency of upward transitions from one facies to another in a vertical sequence is tabulated in a matrix table. Each cell contains the frequency of transitions from the facies states denoted by the rows of the matrix to the facies state denoted by the columns of the matrix. All recent applications of Markov analysis have employed an "embedded" transition matrix in which transitions from one facies state to the same facies state are considered unobservable or undefined. Therefore these cells, which make up the principal diagonal of the matrix, are constrained to zeros.

A matrix of expected frequencies is calculated to provide a model of randomness or independence, i.e. the absence of the Markov property in the data sequence. The expected transition frequencies are then subtracted from the observed transition frequencies, yielding a matrix of differences, termed the "residuals". Earlier users of the Markov technique for stratigraphic data used the magnitude of the positive residuals as an indication of significant non-random transitions (Ethier, 1975; Cant and Walker, 1976; Johnson, 1984). Many authors have suggested testing the residuals matrix for non-randomness using a χ^2 test (Anderson and Goodman, 1957; Harbaugh and Bonham-Carter, 1970). However, it has been suggested that the χ^2 test be used with caution in evaluating embedded matrices, because the constraint that some cells must be 0 means that a matrix of expected frequencies can not truly be considered as random (Schwarzacher, 1975). More recently, Harper (1984a) suggested that the residuals be evaluated for significant deviation from randomness using binomial probability tests of significance. He demonstrated that large residuals may not necessarily be statistically significant, and conversely that smaller residuals may have great significance.

Another method for testing the residuals matrix for significance has been proposed by Türk (1979). One may test for outliers by assuming that the residuals are normally distributed and standardising them to mean 0 and standard deviation 1. Then 90% of the residuals should lie within ±1.6 standard deviations of the mean, approximately 95% should lie within ±2 standard deviations, and approximately 99.5% should lie within ±3 standard deviations. One can thus assign a probability to the occurrence of large residuals.

The method of calculating the expected frequency matrix has been a topic of discussion in recent literature (Powers and Easterling, 1982; Carr, 1982; Türk, 1982; Jinsheng, 1984; Harper, 1984a, 1984b). The two most widely used and generally accepted methods are that of row-scaling (Gingerich-Read method) and iterative proportional fitting (Goodman, 1968).

In the row-scaling technique random probabilities or expected frequencies are calculated for the transition *from* a specific facies *to* all the others. Each facies row (the initial facies state) is considered independently from the other rows, and the transition probabilities for that row must sum to 1. The row-scaling technique lends itself to a significance analysis of the residuals using Harper's (1984a) method of binomial probabilities.

It has been pointed out, however, that using row-scaling to obtain the expected frequency matrix fails to preserve the columnar totals of the observed frequency matrix (Powers and Easterling, 1982; Carr, 1982; Türk, 1982). This means that the expected probabilities for transition *to* a particular facies *from* each of the others (the columns) do not sum to 1. Thus the matrix as a whole is not balanced and the residuals should not be tested for independence using a χ^2 significance test. On the other hand, if it is considered that one is examining the probability of a transition *to* a new state *from* an initial state, then it is the row sums that must be preserved, and it is the row probabilities that must sum to 1. Columns are therefore not a factor in the transition probabilities. As Harper (1984a) points out, one may also examine the probability of having come *from* a particular facies state *to* the present state. This implies that given two facies states, A and B, the probability of a transition *to* facies B if the present state is facies A is not necessarily the same as the probability of transition *from* facies A if the present state is facies B. The latter is the equivalent to looking for a Markovian process down a stratigraphic sequence rather than up. To examine this reversed probability would require column-scaling to obtain the expected frequencies, and the application of Harper's (1984a) binomial probability significance testing to the columns of the residuals matrix rather than the rows. Given this dichotomy, it does not seem appropriate that the rows and columns be balanced, and therefore the χ^2 test for independence of the residuals matrix as a whole should not be applied in conjunction with the Gingerich-Read row-scaling method for expected frequencies.

Iterative proportional fitting to derive a balanced independent transition frequency matrix solves the problem of preserving column totals. However, as the preceding discussion points out, there is an apparent loss of information in that there is an implicit assumption in the method that the expected transition frequencies down the sequence are the same as the expected transition frequencies up the sequence. Furthermore, because of the embedded nature of the matrix it is still advisable to use the χ^2 test for independence with caution (Schwarzacher, 1975).

In this study, both methods of Markov analysis were applied to the data: 1) row-scaling of Gingerich-Read using Harper's binomial probability test for significance, and 2) iterative proportional fitting of Goodman, using both a χ^2 test and Türk's standardised residuals for significance. The results from both methods were similar in that both picked out the same transitions as being the most significant.

It should be pointed out that Markov analysis applied to a series of laterally equivalent stratigraphic intervals has some implications that makes it different from an application of the method to a single continuous vertical succession:

1) It cannot be said that Markov analysis is testing for cyclicity in the data, because the transitions are from a series of repeated lateral samples over essentially the same interval.

2) Because each core is a discrete succession, there are a greater number of incomplete transitions, i.e. one at the base and one at the top of each core. This has a similar effect as encountering many covered intervals in a continuous vertical succession.

3) Lateral stationarity becomes a concern rather than vertical stationarity (stationarity can be defined as the persistence of the transition probabilities regardless of where in the succession they are observed).

4) Even though a particular transition may be vertically random, that transition may be laterally persistent, and will show significance when tallied from well to well. The areally persistent transition will be emphasised (Miall, 1973; Powers and Easterling, 1982). This means that by testing for the Markov property in a set of transitions from repeated lateral samples, one is really testing for the lateral persistence of a transition. As such, a series of significant transitions implies a "typical" vertical succession through a particular unit (even though the vertical successions may be laterally diachronous).

Because the vertical transitions may still be random in a cyclic sense, any derived significant Markov chain cannot be used as a facies model in the manner described by Walker (1979). Also, a finding of significant transition probability residuals empirically implies a measure of lateral stationarity, while a finding of independence in the residual matrix may imply non-stationarity. Wells (1989) discusses other situations where analysing laterally equivalent sections may be appropriate.

RESULTS

Each of the predefined facies intervals was given a unique number from 1 to 140 for ease of identification on the cluster dendrogram.

Results of Q-Mode Cluster Analysis

The total misclassified intervals for different combinations of similarity coefficient and fusion transformation functions was tallied based on the assumption that the original subjective classification approaches an ideal (Table IV-1). Three combinations of functions were discarded from further testing because the calculated similarity coefficients consisted of only a very few discrete values. For example, in the worst case all entities were clustered together at only five different values of the similarity coefficient. All three of these discarded tests used the single linkage (nearest neighbour) procedure for fusion transformations of the similarity coefficients.

Of the seven remaining test runs, four formed a group giving the lowest misclassification scores (Table IV-1): simple matching with complete linkage, similarity ratio (Jaccard) with complete linkage, similarity ratio (Jaccard) with unweighted pair group average linkage, and Euclidian distance with error sum of squares (Ward's method). Amongst these four the optimum choice became more subjective.

Two attributes, rhizoliths and synaeresis cracks are diagnostic of very specific environmental conditions. An optimum clustering technique should classify all facies intervals in which these occur into discrete clusters, and they should be linked to other clusters at a relatively late stage. All four test runs classified rhizoliths into a discrete cluster early in the analysis, however the Jaccard with complete linkage method also tended to fuse this cluster with others at an early stage.

Ward's method (Euclidian distance with error sum of squares) performed the best in clustering entities with synaeresis cracks, classifying them into two groups, one with low diversity, and one with high diversity (Fig. IV-3). Ward's method also displayed the greatest relative magnitude in separation of the cluster similarity coefficients. The other three methods produced several clusters containing very few entities, sometimes only one or two, that remained unfused until the later stages of the analysis. Given all

Similarity Coefficient	Fusion Transformation Function	"Misclassification" Score
Simple Matching	Complete Linkage (Furthest Neighbour)	63
Simple Matching	Average Linkage (Unweighted Pair Group)	69
Similarity Ratio (Jaccard)	Complete Linkage (Furthest Neighbour)	60
Similarity Ratio (Jaccard)	Average Linkage (Unweighted Pair Group)	57
Error Sum of Squares	Complete Linkage (Furthest Neighbour)	71
Error Sum of Squares	Average Linkage (Unweighted Pair Group)	71
Euclidian Distance	Ward's Method (Error Sum of Squares)	62

Table IV-1. Misclassification scores for various combinations of similarity coefficient and fusion transformation function: The original subjective classification of the facies intervals into 11 trace fossil suites is used as a control. The facies intervals were fused until 11 clusters remained. The assertion is made that the optimum combination of similarity coefficient and fusion transformation function is the one that clusters the data into a classification that comes closest to the subjective classification. The subjectively assigned trace fossil suites were tallied for each cluster. The one with the highest frequency was considered to be the "correct" class. The "misclassified" facies intervals were then summed to give a "misclassification" score.

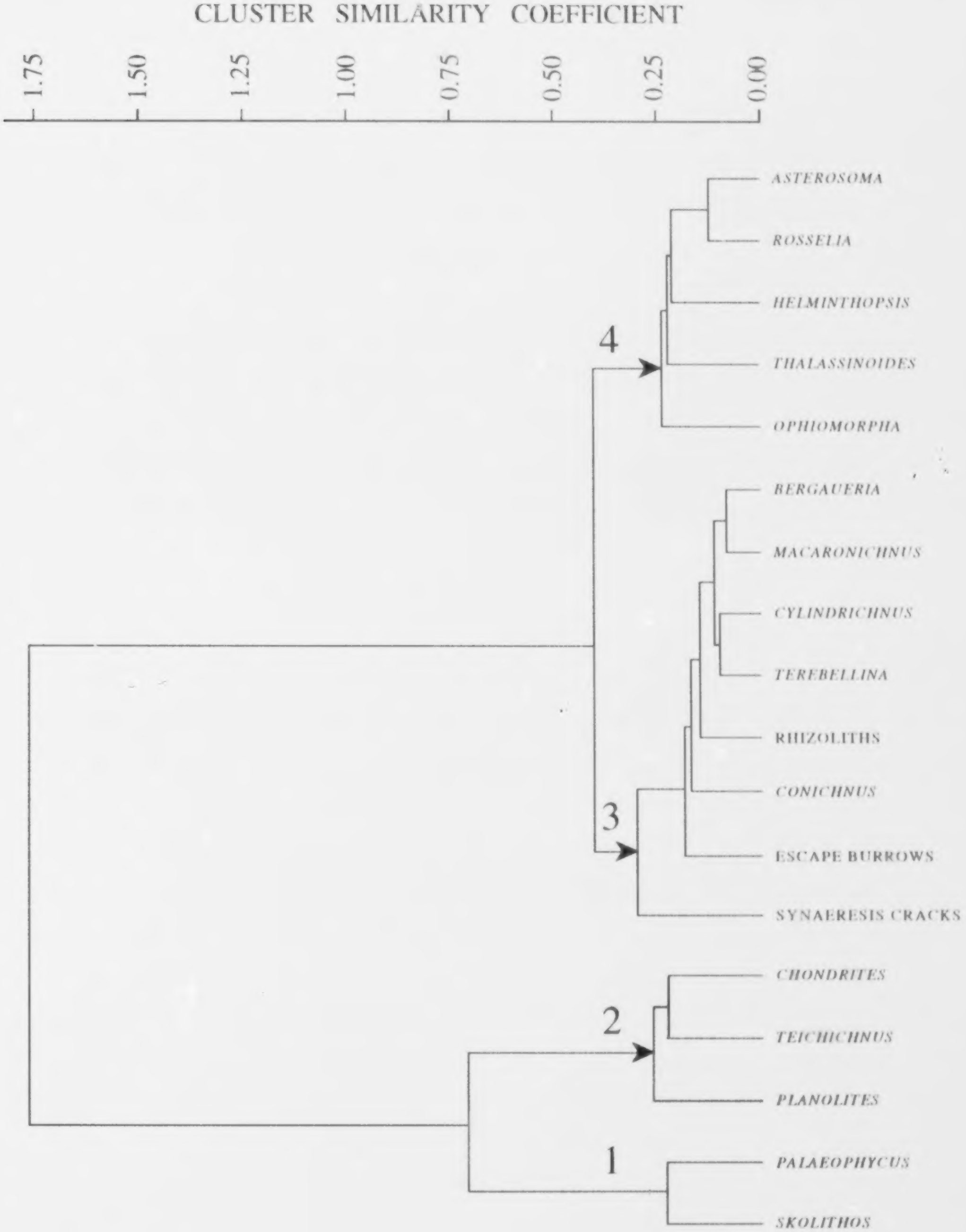

Figure IV-3. R-mode cluster analysis utilising Ward's method. Arrows indicate the four clusters judged to be significant associations

of these considerations, Ward's method was chosen as the optimum method for further analysis.

Kitchell and Clark (1979) and May and Jones (1982) have also used Ward's method for cluster analysis using ichnological and lithological data respectively, although neither mentioned their criteria for the choice. Bjerstedt (1988), on the other hand, utilised the Jaccard coefficient to recognise major ichnofacies in the Mississippian Price Formation of West Virginia, but his data contained no units that lacked ichnofossils.

The division of the entities into an optimum number of logical and workable classes based on the Q-mode analysis is a matter requiring some judgment. As an aid in determining a suitable number of classes, the graph displaying the change in magnitude of the difference in similarity coefficient with successive fusion cycles should be examined (Fig. IV-4). The first large magnitude discontinuity occurs with fusion of nine clusters into eight, signifying that nine may be a reasonable, natural choice for the optimum number of classes. This deduction is further reinforced by the results of the Mojena stopping rule. The deviation of the similarity coefficient from the mean passes into the upper tail of the distribution at the fusion of nine clusters into eight.

Results of R-Mode Cluster Analysis

Regardless of which combination of similarity functions was used in the R-mode clustering trials, four main associations (Fig. IV-3) persistently recurred: 1) *Skolithos* is associated with *Palaeophycus*, 2) *Chondrites* and *Teichichnus* are associated with *Planolites*, 3) *Asterosoma*, *Rosselia*, *Helminthopsis*, *Thalassinoides* and *Ophiomorpha* are associated together and the remaining forms make up a fourth cluster. Because these associations showed persistence from method to method, they were deemed to be highly significant. The R-mode cluster analysis using Ward's method (Fig. IV-3) was chosen for further analysis in order to be consistent with the preferred method of the Q-mode analysis.

Contingency Table

A two-way contingency table was constructed by plotting entities along

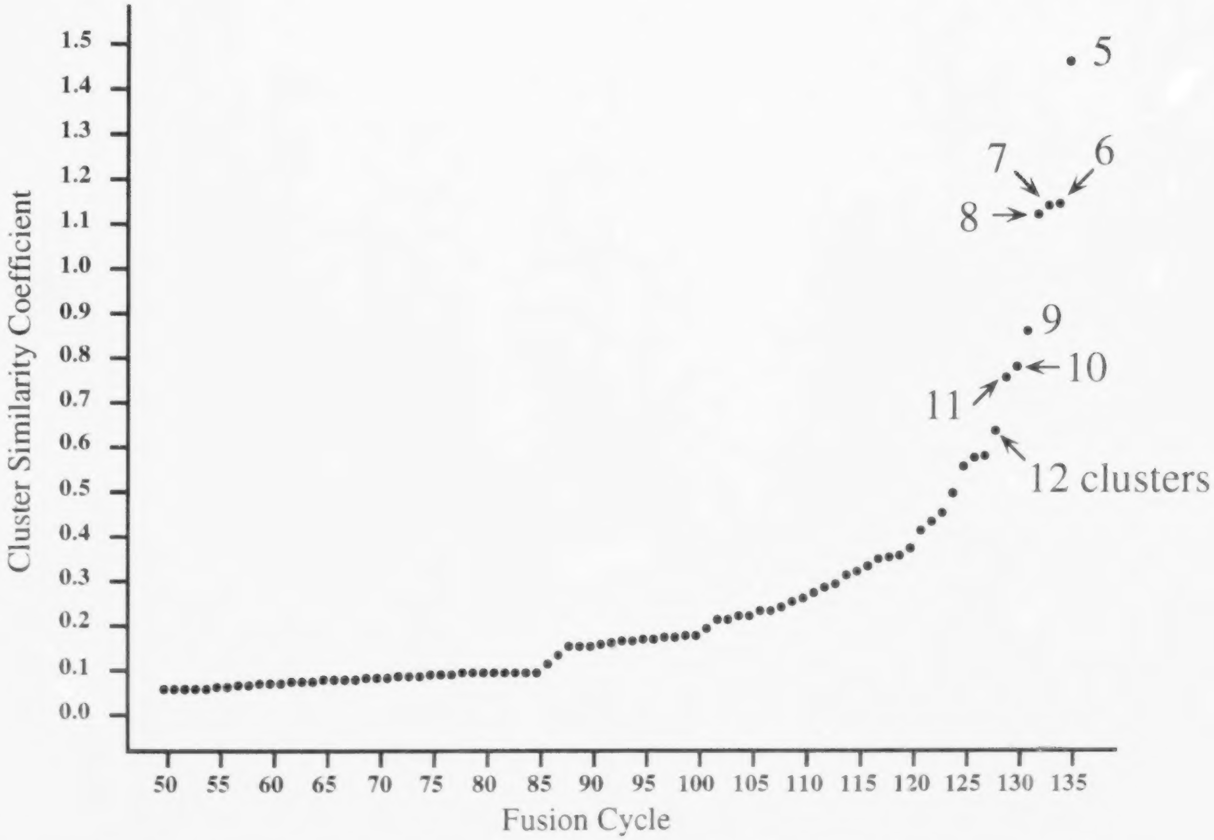

Figure IV-4. Cluster similarity coefficient plot of the fused clusters for successive fusion cycles illustrating large discontinuities that suggest an optimum number of clusters. The point labels marking the later stage fusion are the number of clusters remaining following each fusion cycle. The first relatively large discontinuity occurs with the fusion of 9 clusters to 8. This indicates that a 9 cluster classification scheme should be examined for suitability.

one axis, and attributes along the other (Fig. IV-5). Both the entities and the attributes are ordered along their respective axes according to the hierarchy produced by the cluster analyses. The result is a display that helps one visualise the structure of the data. The attributes are shown grouped into their four associations.

Lines are drawn on the contingency table separating the entities into nine classes and the attributes into 4 classes. The intersection of these classes divide the table into a logical structure. Note that facies intervals containing rhizoliths and synaeresis cracks occur for the most part in separate classes and that even though these two attributes were associated in the R-mode analysis, they are differentiated by the contingency table.

The label number assigned to each class refers arbitrarily to the identification number of the first facies interval occurring in that class (i.e. the cluster 'seed'). On close examination, classes 4 and 7, separated by a dashed line, appear quite similar: both have a high diversity and are dominated by the presence of associations 1, 2 and 4. These two classes were judged to be relatively similar, and for all further analyses were considered to be members of a single class, class 4. Based on these considerations, the division of the data into 8 classes therefore appears to be the most acceptable, and the most workable.

Because it can be assumed that these eight classes represent distinct paleoecological conditions, they can properly be designated as "ichnocoenoses". Table IV-2 tabulates the mean diversity and thickness of each ichnocoenosis. The measure of diversity is used here in its simplest form: the number of different ichnotaxa occurring in an ichnocoenosis interval (Kitchell, 1979). Rhizoliths and synaeresis cracks are of course not considered in the measure of diversity.

Results of Markov Analysis

The eight ichnocoenoses determined by the cluster analysis constitute the input states for an embedded Markov analysis. Several scour surfaces had been recorded on the core logs, and these were included as a ninth state. De Raaf *et al* (1965) and Walker (1979) have recommended this procedure because of the uncertainties regarding transitions across eroded contacts. One

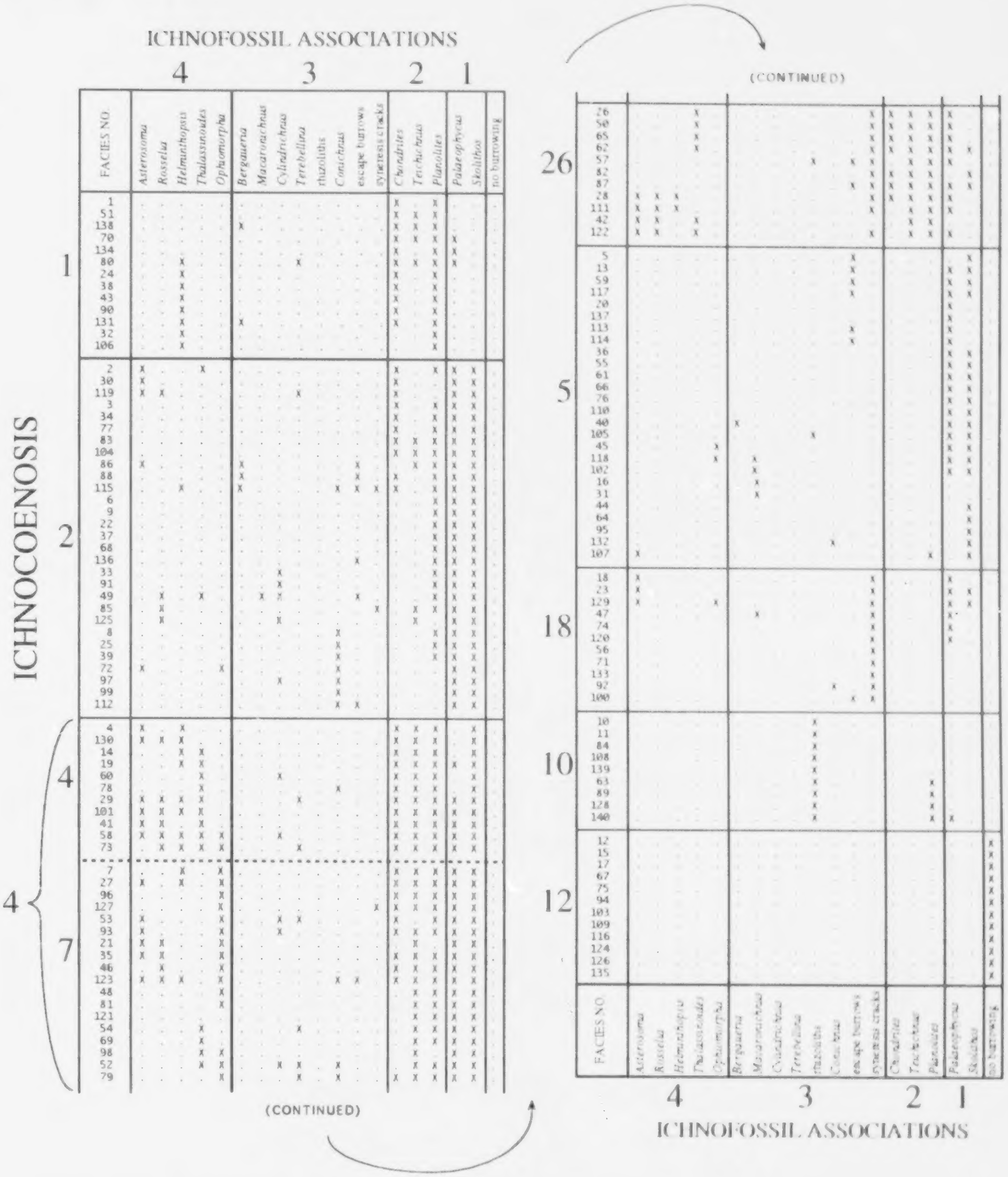
ICHNOFOSSIL ASSOCIATIONS
4
3
2
1
FACIES NO.
Asterosoma
Rosselia
Helminthopsis
Thalassinoides
Ophiomorpha
Bergaueria
Macaronichnus
Cylindrichnus
Terebellina
rhizoliths
Conichnus
escape burrows
syneresis cracks
Chondrites
Teichichnus
Planolites
Palaeophycus
Skolithos
no burrowing
ICHNOCOENOSIS
1
2
4
7
4
26
5
18
10
12
(CONTINUED)
(CONTINUED)
ICHNOFOSSIL ASSOCIATIONS

Figure IV-5. Contingency table of entities plotted along the long axis and attributes plotted along the short axis. Entities and attributes are ordered using the hierarchy developed by the cluster analyses. Lines divide the attributes into 4 ichnofossil associations, and the entities into 8 ichnocoenoses. The entities were at first classified into 9 ichnocoenoses. Ichnocoenoses 4 and 7, separated by dashed lines, were subsequently judged to be relatively similar and were combined to form a single ichnocoenosis for all further analyses.

ICHNOCOENOSIS	N	DIVERSITY MEAN	DIVERSITY STANDARD DEVIATION	THICKNESS (m) MEAN	THICKNESS (m) STANDARD DEVIATION
1	13	3.20	1.09	3.80	1.83
2	27	4.65	1.51	3.42	2.60
4	29	7.14	1.85	4.15	2.88
5	22	2.12	0.84	3.75	2.69
10	11	0.56	0.73	4.27	4.40
12	10	0.00	0.00	2.54	1.49
18	9	1.45	1.37	4.04	3.39
26	11	5.27	1.01	3.49	2.07

Table IV-2. Sample statistics for the diversity and thickness of each of the ichnocoenoses derived from cluster analysis. The measurement of diversity used here is the number of different ichnotaxa recognised in a facies interval.

other adjustment to the data was made. Several facies intervals recorded as containing no burrowing did contain coal beds that were obviously not detrital plant matter because they merged gradationally into underlying shales. These intervals were reclassified as if they contained rhizoliths, and were assigned to ichnocoenosis 10 rather than ichnocoenosis 12.

The transition frequency matrix and the transition probability matrix are displayed in Table IV-3. There were 106 transitions. Row totals and column totals for many of the facies are different because of the nature of the data: 22 discrete sequences with incomplete transitions at the base and top of each. Note for instance, that there are a total of only 3 transitions *to* state 10, but 11 transitions *from* state 10. This is a reflection of the fact that the base of the Bluesky cores tend to terminate in this facies interval.

The results of the Gingerich-Read row scaling method with Harper's binomial probability for significance are shown in Table IV-4. The transitions with significance at the 90% confidence level or better show that a rather simple Markov process is evident in the data (Fig. IV-6a).

The results of Goodman's iterative proportional fitting method using Türk's standardised residuals is shown in Table IV-5. The χ^2 statistic is 82.90. The critical value of the 95% upper confidence limit of the χ^2 distribution for 63 degrees of freedom is 82.53. Therefore the null hypothesis, that the residuals matrix is independent, can be rejected. The standardised residuals matrix (Table IV-5c) shows that several observed transition probabilities are considered outliers as they lie in the tails of a normal distribution outside the 90% confidence area. The largest transition outliers are summarised in Fig. IV-6b. They are essentially the same as those deduced from the Gingerich-Read method. The weakest of these transitions is the transition from ichnocoenosis 1 to ichnocoenosis 4, which is slightly less than the 90% confidence limit using the row-scaling method, falling to a 86.4% confidence limit using iterative proportional fitting.

DISCUSSION

Ichnofossil Associations from R-mode Cluster Analysis

Ichnofossil association 1 (Fig. IV-3) belongs to the *Skolithos* ichnofacies and consists of two ichnotaxa, *Palaeophycus* and *Skolithos*. They almost

A. TRANSITION FREQUENCY MATRIX

FACIES	1	2	4	5	10	12	18	26	SS	ROW TOTAL
1		0	3	0	0	0	1	1	1	6
2	6		3	5	0	3	0	3	1	21
4	0	7		5	0	1	6	2	2	23
5	3	3	6		0	3	0	1	3	19
10	2	5	1	1		0	0	1	1	11
12	0	1	2	3	2		0	0	0	8
18	0	4	0	1	0	1		0	1	7
26	0	3	4	3	1	0	0		0	11
SS	1	1	2	3	0	2	0	1		10
TOTAL	12	24	21	21	3	10	7	9	9	116

B. OBSERVED TRANSITION PROBABILITY MATRIX

FACIES	1	2	4	5	10	12	18	26	SS
1		0.0000	0.5000	0.0000	0.0000	0.0000	0.1667	0.1667	0.1667
2	0.2857		0.1429	0.2381	0.0000	0.1429	0.0000	0.1429	0.0476
4	0.0000	0.3043		0.2174	0.0000	0.0435	0.2609	0.0870	0.0870
5	0.1579	0.1579	0.3158		0.0000	0.1579	0.0000	0.0526	0.1579
10	0.1818	0.4545	0.0909	0.0909		0.0000	0.0000	0.0909	0.0909
12	0.0000	0.1250	0.2500	0.3750	0.2500		0.0000	0.0000	0.0000
18	0.0000	0.5714	0.0000	0.1429	0.0000	0.1429		0.0000	0.1429
26	0.0000	0.2727	0.3636	0.2727	0.0909	0.0000	0.0000		0.0000
SS	0.1000	0.1000	0.2000	0.3000	0.0000	0.2000	0.0000	0.1000	

Table IV-3. Observed ichnocoenoses transition statistics used as input to Markov analyses.

A. EXPECTED (RANDOM) TRANSITION PROBABILITY MATRIX

FACIES	1	2	4	5	10	12	18	26	SS
1		0.2308	0.2019	0.2019	0.0288	0.0962	0.0673	0.0865	0.0865
2	0.1304		0.2283	0.2283	0.0326	0.1087	0.0761	0.0978	0.0978
4	0.1263	0.2526		0.2211	0.0316	0.1053	0.0737	0.0947	0.0947
5	0.1263	0.2526	0.2211		0.0316	0.1053	0.0737	0.0947	0.0947
10	0.1062	0.2124	0.1858	0.1858		0.0885	0.0619	0.0796	0.0796
12	0.1132	0.2264	0.1981	0.1981	0.0283		0.0660	0.0849	0.0849
18	0.1101	0.2202	0.1927	0.1927	0.0275	0.0917		0.0826	0.0826
26	0.1121	0.2243	0.1963	0.1963	0.0280	0.0935	0.0654		0.0841
SS	0.1121	0.2243	0.1963	0.1963	0.0280	0.0935	0.0654	0.0841	

B. RESIDUALS (OBSERVED MINUS EXPECTED) MATRIX

FACIES	1	2	4	5	10	12	18	26	SS
1		-0.2308	0.2981	-0.2019	-0.0288	-0.0962	0.0994	0.0801	0.0801
2	0.1553		-0.0854	0.0098	-0.0326	0.0342	-0.0761	0.0450	-0.0502
4	-0.1263	0.0517		-0.0037	-0.0316	-0.0618	0.1872	-0.0078	-0.0078
5	0.0316	-0.0947	0.0947		-0.0316	0.0526	-0.0737	-0.0421	0.0632
10	0.0756	0.2422	-0.0949	-0.0949		-0.0885	-0.0619	0.0113	0.0113
12	-0.1132	-0.1014	0.0519	0.1769	0.2217		-0.0660	-0.0849	-0.0849
18	-0.1101	0.3512	-0.1927	-0.0498	-0.0275	0.0511		-0.0826	0.0603
26	-0.1121	0.0484	0.1674	0.0765	0.0629	-0.0935	-0.0654		-0.0841
SS	-0.0121	-0.1243	0.0037	0.1037	-0.0280	0.1065	-0.0654	0.0159	

C. PROBABILITY OF OBSERVED OR GREATER NUMBER OF TRANSITIONS OCCURRING

FACIES	1	2	4	5	10	12	18	26	SS
1		-0.2072	0.1013	-0.2584	-0.8389	-0.5452	0.3417	0.4190	0.4190
2	0.0469		-0.2600	0.5415	-0.4985	0.4035	-0.1898	0.3386	-0.3772
4	-0.0448	0.3574		-0.6001	-0.4781	-0.2870	0.0054	-0.6261	-0.6261
5	0.4372	-0.2547	0.2286		-0.5435	0.3230	-0.2336	-0.4510	0.2664
10	0.3290	0.0634	-0.3658	-0.3658		-0.3609	-0.4949	0.5987	0.5987
12	-0.3825	-0.4285	0.4911	0.1989	0.0200		-0.5789	-0.4917	-0.4917
18	-0.4420	0.0463	-0.2236	-0.5970	-0.8225	0.4901		-0.5470	0.4530
26	-0.2702	0.4628	0.1530	0.3702	0.2686	-0.3398	-0.4751		-0.3804
SS	-0.6888	-0.3069	0.6128	0.3109	-0.7525	0.2387	-0.5083	0.5846	

NOTE: A "negative" probability represents the probability of the observed or FEWER number of transitions occurring

Table IV-4. Results of Markov analysis using row-scaling to calculate expected transition probabilities and using the binomial probability test for significance. Large, significant residuals are outlined.

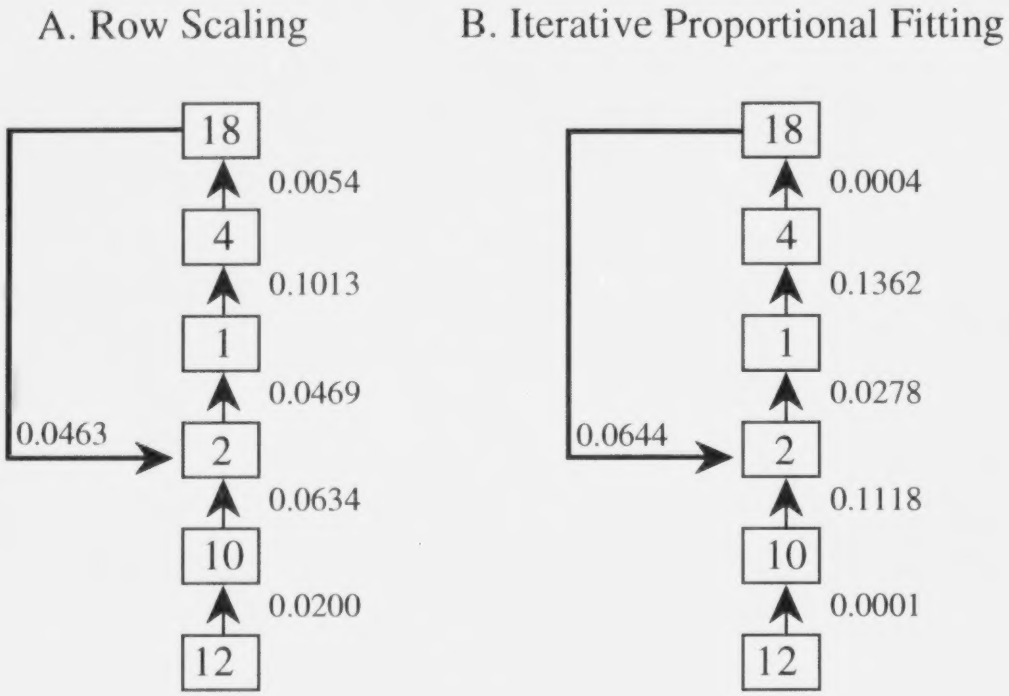
A. Row Scaling
B. Iterative Proportional Fitting
18
0.0054
4
0.1013
1
0.0469
0.0463
2
0.0634
10
0.0200
12
18
0.0004
4
0.1362
1
0.0278
0.0644
2
0.1118
10
0.0001
12

Figure IV-6. Markov chain of the most significant ichnocoenosis transitions. Box numbers are the ichnocoenoses identified in the cluster analysis:

A. Gingerich-Read method of row-scaling with Harper's binomial probability test of significance. Level of significance is the probability of the observed frequency of transitions if the transitions were truly random.

B. Goodman's iterative proportional fitting method with Türk's normalised residuals. Level of significance is the probability of obtaining the calculated residual if the residuals are normally distributed.

A. IPF EXPECTED (RANDOM) TRANSITION PROBABILITY MATRIX

FACIES	1	2	4	5	10	12	18	26	SS
1		1.46	1.30	1.24	0.16	0.52	0.36	0.48	0.48
2	2.51		5.29	5.05	0.65	2.12	1.47	1.96	1.94
4	2.66	6.32		5.36	0.69	2.26	1.56	2.08	2.06
5	2.18	5.17	4.59		0.56	1.84	1.28	1.70	1.69
10	1.05	2.49	2.21	2.11		0.89	0.62	0.82	0.81
12	0.81	1.92	1.71	1.63	0.21		0.47	0.63	0.63
18	0.69	1.64	1.45	1.39	0.18	0.58		0.54	0.53
26	1.10	2.62	2.33	2.22	0.29	0.93	0.65		0.86
SS	1.00	2.38	2.12	2.02	0.26	0.85	0.59	0.78	

4 iterations needed for convergence to 0.1%

B. RESIDUALS (OBSERVED MINUS EXPECTED) MATRIX

FACIES	1	2	4	5	10	12	18	26	SS
1		-1.46	$\boxed{1.70}$	-1.24	-0.16	-0.52	0.64	0.52	0.52
2	$\boxed{3.49}$		-2.29	-0.05	-0.65	0.88	-1.47	1.04	-0.94
4	-2.66	0.68		-0.36	-0.69	-1.26	$\boxed{4.44}$	-0.08	-0.06
5	0.82	-2.17	1.41		-0.56	1.16	-1.28	-0.70	1.31
10	0.95	$\boxed{2.51}$	-1.21	-1.11		-0.89	-0.62	0.18	0.19
12	-0.81	-0.92	0.29	1.37	$\boxed{1.79}$		-0.47	-0.63	-0.63
18	-0.69	$\boxed{2.36}$	-1.45	-0.39	-0.18	0.42		-0.54	0.47
26	-1.10	0.38	1.67	0.78	0.71	-0.93	-0.65		-0.86
SS	-0.00	-1.38	-0.12	0.98	-0.26	1.15	-0.59	0.22	

CHI SQUARE STATISTIC = 82.90 WITH 63 DEGREES OF FREEDOM

C. STANDARDISED RESIDUALS

FACIES	1	2	4	5	10	12	18	26	SS
1		-1.21	$\boxed{1.49}$	-1.11	-0.40	-0.72	1.06	0.75	0.76
2	$\boxed{2.20}$		-1.00	-0.02	-0.81	0.60	-1.21	0.74	-0.68
4	-1.63	0.27		-0.15	-0.83	-0.84	$\boxed{3.55}$	-0.06	-0.04
5	0.56	-0.95	0.66		-0.75	0.85	-1.13	-0.54	1.01
10	0.93	$\boxed{1.59}$	-0.82	-0.76		-0.94	-0.78	0.20	0.21
12	-0.90	-0.66	0.23	1.08	$\boxed{3.91}$		-0.69	-0.79	-0.79
18	-0.83	$\boxed{1.85}$	-1.21	-0.33	-0.42	0.55		-0.73	0.64
26	-1.05	0.23	1.09	0.52	1.33	-0.97	-0.80		-0.92
SS	-0.00	-0.90	-0.08	0.69	-0.51	1.25	-0.77	0.24	

Table IV-5. Results of Markov analysis using Iterative Proportional Fitting (IPF) to calculate expected transition frequencies and using standardised residuals as a test of significance. Large residuals are outlined.

invariably occur together, and are abundant within the ichnocoenoses they characterise. (Abundance is used here as a relative term indicating the proportion of facies intervals in which a form was recognised). The presence of this association implies moderate to high energy levels over a loose, unconsolidated, sandy substrate.

Ichnofossil association 2 consists of *Chondrites, Teichichnus,* and *Planolites,* all reflecting deposit feeding behaviour. They are commonly found together, but in some intervals one or two ichnotaxa may dominate to the exclusion of the others. *Planolites* in particular appears to be non-specific, and occurs in almost every ichnocoenosis at least rarely but usually abundantly. This association represents a *Cruziana* ichnofacies and implies relatively quiet energy conditions, below normal wave base, in a loose, unconsolidated, fine-grained substrate.

Ichnofossil association 3 is distinctive in that it seems to be a cluster of a non-associated ichnotaxa. They are overall rarer than ichnotaxa in the other associations, and there is no obvious tendency for them to occur together. In fact the opposite is true. This is an artifact of the similarity coefficient function that was used which places significance on the mutual absence of an attribute, combined with the fact that many of these attributes occur to the exclusion of almost all others or occur in numbers that are too low to contribute significantly to the classification scheme.

Ichnofossil association 4 represents dwellings (*Thalassinoides* and *Ophiomorpha*) as well as the behaviour of deposit feeders (*Asterosoma* and *Rosselia*) and grazers (*Helminthopsis*). They do not all tend to occur together. Typically there are only one or two of these ichnotaxa together in any one facies interval. Except in ichnocoenosis 4, they cannot be considered abundant, and in some cases one or two ichnotaxa may be characteristically abundant in a specific ichnocoenosis, for instance *Helminthopsis* in ichnocoenosis 1. The occurrence of ichnotaxa having distinct linings (*Asterosoma, Rosselia* and *Ophiomorpha*), suggests the presence of a marginally or periodically high energy levels in a loose, dominantly arenaceous, non-cohesive substrate. Deposit feeding behaviour implies the presence of organic matter in the substrate.

Ichnocoenoses from Q-Mode Cluster Analysis

Ichnocoenosis 1 is dominated by ichnofossil association 2, the deposit feeding traces *Chondrites, Planolites* and *Teichichnus. Helminthopsis,* a grazing deposit feeding trace from ichnofossil association 4 is also relatively abundant. This ichnocoenosis is thus represented almost exclusively by ichnogenera comprising the *Cruziana* ichnofacies. Diversity is moderate, averaging 3.2 ichnotaxa per facies interval. Ichnocoenosis 1 can be interpreted to be from a lower shoreface, open marine environment, well below normal wave base, possibly below storm wave base, or at least sheltered from storm waves.

Every facies interval assigned to ichnocoenosis 2 contains both *Palaeophycus* and *Skolithos* ichnofossil association 1. *Chondrites, Teichichnus* and especially *Planolites* of ichnofossil association 2 are also quite common, although not universally present. All other ichnotaxa may also be present but are generally rare, occurring in only one or two of the facies intervals. Diversity is moderately high with an average of 4.6 ichnotaxa per facies interval. This ichnocoenosis is a relatively high diversity *Skolithos* ichnofacies but with a significant *Cruziana* ichnofacies component. It may be interpreted as representing a middle shoreface, open marine environment, probably well within storm wave base, and perhaps extending up into normal wave base.

Ichnocoenosis 4 has the highest diversity of all, averaging 7.1 ichnotaxa per facies interval. It is dominated by ichnofossil associations 1 and 2, but ichnofossils from association 4 are also very common. This appears to be an ichnocoenosis containing a mixed *Skolithos* and *Cruziana* ichnofacies suite, possibly from a middle shoreface environment. Alternatively this ichnocoenosis may indicate alternating periods of low energy and high energy, perhaps within the influence of periodic storm activity, but below fair weather wave base. The presence of the *Skolithos* ichnofacies may also indicate an opportunistic behaviour pattern (Pemberton and Frey, 1984a).

Ichnocoenosis 26 is somewhat similar to ichnocoenosis 4, in that it has a relatively high diversity, averaging 5.3 ichnotaxa per interval, and is not dominated by any one ichnofossil association. Ichnofossils from association 2 are most abundant, but association 1 and 4 are well represented by various

This could be indicative of a more cohesive substrate and somewhat lower energy levels than ichnocoenosis 4. A key environmental indicator in ichnocoenosis 26 is the abundant development of synaeresis cracks. All but 1 of the facies intervals assigned to this ichnocoenosis contains these structures. Synaeresis cracks have been interpreted to indicate periodic mixing of fresh and marine waters (Burst, 1965; Plummer and Gostin, 1981). The associations in this ichnocoenosis may thus periodically experience stressful brackish water conditions, which would place it in or near a marginal marine environment.

Ichnocoenosis 5 has a relatively low diversity (2.1), and consists almost exclusively of *Skolithos* and *Palaeophycus* of ichnofossil association 1. Escape structures and *Macaronichnus* were occasionally recorded, but all other ichnotaxa are rare or absent. A loose, unconsolidated, sandy substrate, in a high energy environment is indicated. This ichnocoenosis may be interpreted as belonging to the upper shoreface.

Ichnocoenosis 18 is characterised by the presence of synaeresis cracks in every facies interval assigned to it. In contrast to ichnocoenosis 26, which also contains abundant synaeresis cracks, it has a very low diversity, averaging 1.45 ichnotaxa per interval. *Palaeophycus* is common, however all other ichnotaxa are rare or absent. As is the case for ichnocoenosis 26, the synaeresis cracks probably indicate the presence of brackish water conditions. The very low diversity suggests that the brackish conditions were a relatively common occurrence, keeping the fauna under a rather constant environment of stress. A marginal marine environment is indicated, possibly estuarine or delta front.

Ichnocoenosis 10 is characterised by the presence of rhizoliths (or coal beds). Mean diversity is extremely low, at only 0.6. The only ichnofossils recorded are occasional *Planolites* and a rare *Palaeophycus*. The rhizoliths indicate marginal to non-marine conditions, possibly swamp or coastal plain environments.

Ichnocoenosis 12 includes all the facies intervals that are barren of ichnofossils, rhizoliths and synaeresis cracks. This may be interpreted as a high energy environment, possibly upper foreshore or beach, or it could also indicate non-marine conditions.

indicate non-marine conditions.

Interpretation of the Bluesky Sequence

The statistically preferred ichnocoenosis sequence through the Bluesky Formation is summarised in Fig. IV-7. The sequence has at its base the non-burrowed ichnocoenosis 12, chosen because there is no significant transition into that state. From here the significant transitions are successively to ichnocoenosis 10 (rhizoliths), ichnocoenosis 2 (high diversity *Skolithos* ichnofacies), ichnocoenosis 1 (*Cruziana* ichnofacies), ichnocoenosis 4 (high diversity mixed *Skolithos* and *Cruziana* ichnofacies), and ichnocoenosis 18 (low diversity with synaeresis cracks).

Ichnocoenosis 18 has a significant transition back to ichnocoenosis 2, and this may be the expression of a cyclic process, however a longer vertical sequence would have to be analysed for the existence of a Markov process before such a conclusion could be made. There are no significant preferred transitions to or from ichnocoenosis 5 (low diversity *Skolithos* ichnofacies), ichnocoenosis 26 (high diversity mixed ichnofacies with synaeresis cracks) or the scoured surfaces. These must therefore be considered statistically "random" transition states, indicating that they are laterally non-persistent. Ichnocoenoses 12 and 10, at the base of the sequence, can be interpreted as the maximum development of a regressive phase. The immediately overlying facies, ichnocoenosis 2, which is the high diversity *Skokithos* ichnofacies interpreted to occur in a middle shoreface, open marine environment, may then be the transgressive phase of the sequence. The succeeding 3 ichnocoenoses can be considered typical of a vertical regressive sequence. From bottom to top: ichnocoenosis 1 is the moderate diversity *Cruziana* ichnofacies of the open marine lower shoreface; ichnocoenosis 4 is the high diversity mixed *Cruziana-Skolithos* ichnofacies of the middle to upper shoreface, probably within the influence of storm activity; and ichnocoenosis 18, which has a low diversity and abundant synaeresis cracks, can be interpreted as indicating brackish water, marginal marine conditions.

Finally, a comment is offered regarding the efficacy of using statistical techniques to interpret geological data. For both techniques used in this study, there were many subjective decisions to be made during the analysis.

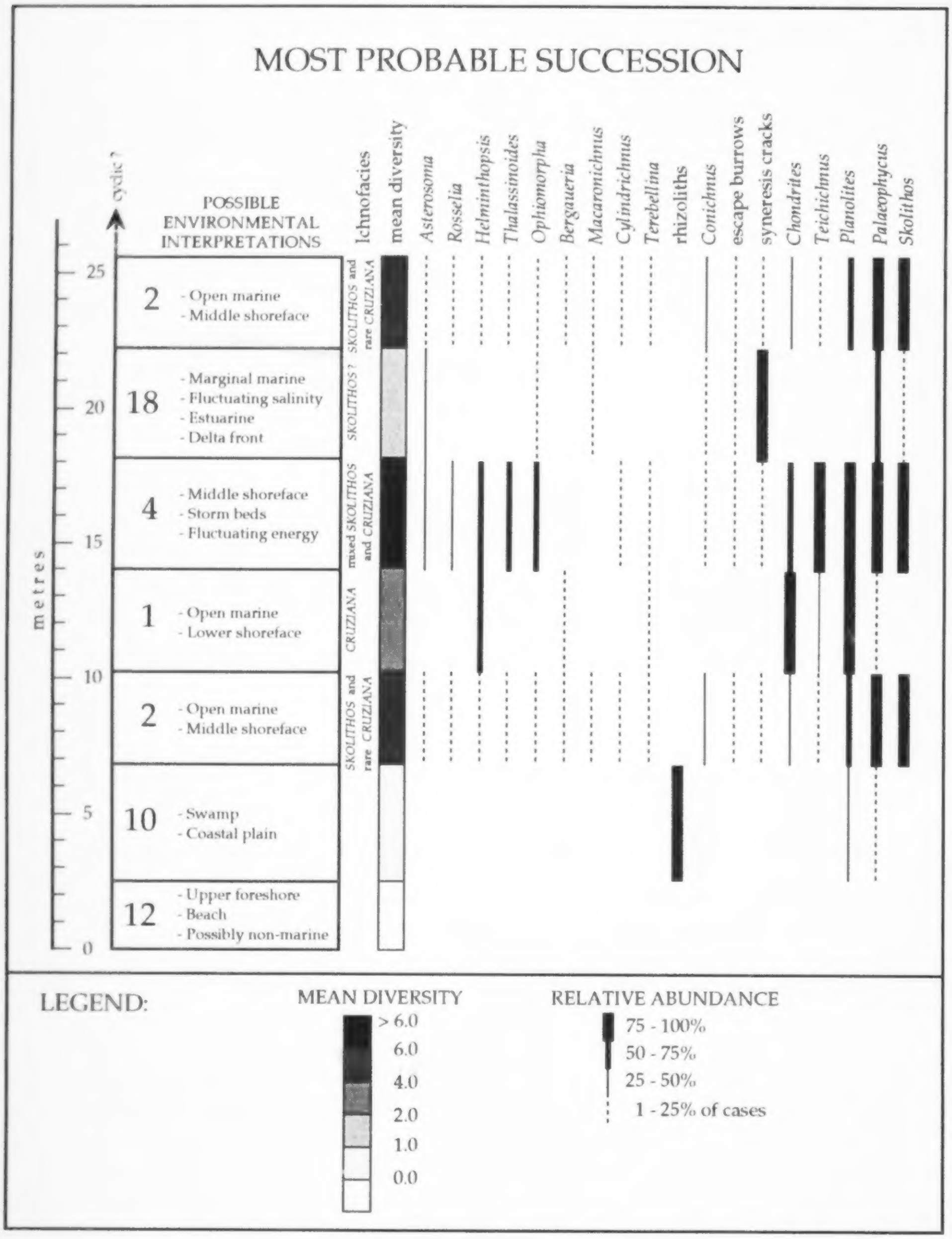

Figure IV-7. Statistically preferred ichnocoenosis succession derived from Markov analysis of the ichnocoenosis clusters, and environmental interpretation for the Bluesky Formation. Interval thickness for each ichnocoenosis is the mean of all occurrences.

Such decisions start even at the data collection phase with the examination of the core, which is an endeavour that depends on the skill and experience of the geologist who does the logging. One must not be deluded into thinking that statistical techniques alone can produce an objective and unique interpretation of the data. This is especially true of non-parametric techniques such as those used here, in which there is no underlying assumption of normality in the data. Statistical methods may be used to examine and explore the data, but the final interpretation still remains a subjective enterprise.

CONCLUSIONS

The application of cluster analysis to ichnofossil data from a series of laterally equivalent subsurface cores satisfactorily distinguishes ichnocoenoses in Q-mode analysis and ichnofossil associations in R-mode analysis. These have proven to be valuable as an aid in deducing paleoenvironments and paleoecological conditions. Based on the control provided by an existing subjective classification into ichnofossil suites, the optimum clustering technique appears to be Ward's method, which incorporates binary Euclidian distance for the similarity coefficient, and error sum of squares for the fusion transformation function. Other functions such as the simple matching coefficient or the Jaccard coefficient with complete linkage performed almost as well. The error sum of squares similarity coefficient, and the single linkage transformation function did not produce acceptable results.

Selection of the optimum number of classes or ichnocoenoses is aided by a contingency table, in which the entities and attributes are ordered by the hierarchy developed in cluster analysis. A further aid is a graph of similarity coefficients versus fusion cycle to outline significant discontinuities that can signal an optimum number of classes. Eight classes appear to be the most logical and workable for this study, and these can be properly termed ichnocoenoses.

Using the eight ichnocoenoses as the transition states, two methods of Markov analysis were applied: the Gingerich-Read method using Harper's binomial probability for significance, and Goodman's iterative proportional fitting method with Türk's standardised residuals. Both give similar results by picking out the same significant ichnocoenosis transitions.

A laterally persistent vertical model for the Bluesky Formation in the study area appears to be that of a nearshore to marginal marine regressive sequence following a sudden transgression over a coastal plain or swamp environment.

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CHAPTER V

ELEMENTS OF A STRATIGRAPHIC FRAMEWORK FOR THE McMURRAY FORMATION IN SOUTH ATHABASCA

INTRODUCTION

Most published studies on the facies and stratigraphy of the McMurray Formation in the Athabasca Oil Sands Deposit have dealt with relatively local areas, typically over a potential production site (Benthin and Orgnero, 1977; James and Oliver, 1977; Nelson and Glaister, 1978; Knight *et al.*, 1981; Dekker *et al.*, 1984; Rennie, 1987; Beckie and McIntosh, 1989). As this study shows, it is understandable that a comprehensive regional stratigraphy has been elusive. Only by using regional data from many hundreds of wells can an underlying stratigraphic scheme be filtered from the overwhelming complexity, and in places, domination, of the stratigraphy by channelised lowstand deposits.This study has found that it is all but impossible to erect a workable stratigraphic scheme based on well or outcrop data from an area the size of a typical oil sands lease.

Only one other notable regional study has been published on the Athabasca Oil sands, that is the ground-breaking work of Flach (1984), whose economic study of the northern, potentially mineable, part of the Athabasca Deposit stands as a technical model for the characterisation of oil sands resources. However regional studies such as this are overwhelmed by the large amount of subsurface data available, primarily geophysical well logs and cores. These data are of many different vintages dating back, in the earliest cases, to the late 19th century. The vast amount of data began to accumulate quickly in the 1960's, and by 1992, there were upwards of 6000 wells penetrating the Athabasca Oil Sands, of which perhaps one fifth have been cored. The accumulation and synthesis of this amount of data forces the regional researcher to use only a sample of the available wells, typically four wells per township, (Flach, 1984; Keith *et al.*, 1988; MacGillivray *et al.*, 1992). The present study was designed to use a database from a much larger sample of data, one well per section (1 section = 1sq mi. = 2.56 sq km).

Previous studies have typically collected and used a sample of digitised geophysical logs to calculate only geotechnical properties and reservoir parameters of the Athabasca Deposit (Flach, 1984; Keith *et al.*, 1988; MacGillivray *et al.*, 1992). The present study was designed around development of microcomputer-based graphics software to display the well logs in a standardised manner and produce stratigraphic cross-sections quickly and interactively using any of over 1700 wells digitised from the study area. Above all else, it is this facility that has allowed the new interpretations presented in this study.

Digitised sedimentology of the cores has also played an important role. Statistical techniques have been utilised for facies analysis, resulting in important evidence that complements the interpretations based on the geophysical well logs.

PREVIOUS STUDIES

The history of sedimentologic studies and interpretations of the Athabasca Deposit has evolved slowly and little advance has been made towards a detailed stratigraphic framework. The early sedimentological studies based on modern methods and models is that of Carrigy, who first documented in detail the sedimentological character of the McMurray Formation and the Wabiskaw Member in a series of papers (Carrigy, 1959a, 1959b, 1962, 1963a, 1963b, 1963c, 1966, 1967, 1971). Carrigy established the informal three-fold stratigraphy of the McMurray consisting of a lower, middle and upper unit (Carrigy, 1959a). This basic stratigraphy has not evolved since then, and remains informal, although the units are often referred to as members. Many other workers have also fit their studies into a 3 fold subdivision (Nelson and Glaister, 1978; Stewart and MacCallum, 1978; James, 1977; Flach, 1984). Yet no one has yet been able to reconcile and correlate the stratigraphy observed in the various studies. Given the acknowledged difficulty in correlating beyond a limited area (Mossop, 1980; Flach, 1984), it seems that most workers are reconciled to let McMurray stratigraphy remain on an informal basis. However one study stands out for recognising widespread, correlatable, radioactive (gamma ray) signatures from wells in a local subsurface study in the central Athabasca Deposit.

Nelson and Glaister (1978) pointed out that within the McMurray Formation there existed at least two correlatable shales, which they believed to be time stratigraphic markers. They used these markers to subdivide the McMurray Formation into three units, each of which could be mapped as a discrete depositional system.

Carrigy (1971) observed large inclined bedsets exposed at the Steepbank River, interpreting them as delta foresets. These well known outcrop exposures are now believed to be inclined heterolithic stratification of point bars in a deep incised channel (Flach and Mossop, 1978). Carrigy (1971, 1973) went on to interpret much of the McMurray Formation in the northern part of the deposit as deltaic and related deposits. His conclusions were based partly on the interpretation that the McMurray Formation was primarily of freshwater origin, except for a marine wedge at the top that thickens towards the north and west. A deltaic model has been proposed in several other studies, the most detailed being that of Nelson and Glaister (1978).

The suggestion that much of the McMurray Formation may have been deposited under estuarine conditions was first proposed by Stewart and MacCallum (Stewart and MacCallum, 1978; Stewart, 1963,1981) after many years of subsurface and outcrop study. They put forth the commonly held interpretation that the McMurray Formation consists of a lower fluvial unit, a thick middle estuarine unit and an upper marine unit, and they mapped these facies over much of the northern part of the deposit. Their detailed work has survived the test of time, and their basic three-fold subdivision is still generally accepted. In many studies their three-fold facies model is equated to the informal three-fold stratigraphic framework of Carrigy (1959a).

An on-going debate concerns the extent of marine influence on the accumulation of McMurray sediments. Early studies classified the environments as either marine, usually a thin wedge near the top, or non-marine, making up the bulk of the middle and lower McMurray (Kidd, 1951; Carrigy, 1971). The influence of brackish/estuarine environments has been proposed in many subsequent studies, (Stewart and MacCallum, 1978; James,1977; Knight *et al.*, 1981; Rennie, 1987). These conclusions have been based on sedimentological observation, and also on the fact that palynological studies reveal that the bulk of the Lower and Middle McMurray (Singh, 1964;

Knight *et al.*, 1981) and in some places virtually the whole of the McMurray Formation (Mossop, 1980) is bereft of marine forms. Large-scale, inclined heterolithic stratification (epsilon cross-strata) that fills deep channels in the McMurray Formation was identified in surface outcrops by Flach and Mossop (Flach and Mossop, 1978, 1985). They interpreted much of the depositional succession, at least of the lower and middle units, as fluvial/non-marine in nature. However, it has been pointed out that nowhere in modern environments is inclined heterolithic stratification associated solely with fluvial environments (Smith,1988), but it has been documented in many modern and Holocene, tidally influenced, river-dominated estuaries (Smith 1988 and references therein). Independent detailed studies of ichnofossils both in outcrop (Pemberton *et al.*, 1982) and in the subsurface (Ranger and Pemberton, 1988; Keith *et al.*, 1988) have corroborated Smith's conclusions and have demonstrated without a doubt that a marine influence exists on the McMurray sediments. This marine signature is imprinted not only on what would be considered the upper McMurray, but the middle McMurray also displays a strong marine influence. This marine signature typically expresses itself as a complex suite of trace fossil forms typical of brackish water conditions with indications of fluctuating salinity. The brackish water ichnofossil suites are recognised in channelised facies (Pemberton *et al.*, 1982; Ranger and Pemberton, 1988) as well as off-channel facies (Keith *et al.*, 1988).

BASIN PALEOTOPOGRAPHY

The McMurray Formation lies directly on a major angular unconformity known as the sub-Cretaceous (or pre-Cretaceous) unconformity. In the Athabasca area, Middle to Upper Devonian carbonates subcrop at the unconformity surface. These carbonate strata dip to the southwest and consequently the subcrop surface exposes successively younger units towards the southwest. The Devonian carbonates are generally porous and are believed in places to constitute a karst surface (Belyea, 1952). The angular discordance between the Cretaceous and the Devonian is so gentle that in outcrop the contact appears conformable. Only by regional mapping is the angular relationship evident. The unconformity is a hard, indurated surface. It can be considered as the basement for the Lower Cretaceous succession and no doubt had a profound effect on the distribution of facies in the McMurray Formation. The topography on this erosional surface is therefore of vital importance, because it is on this surface that the reservoir rocks of the Athabasca Oil Sands Deposit were deposited.

The sub-Cretaceous unconformity surface can be modelled by mapping the thickness of a suitable interval whose base lies directly on the unconformity surface. If it is assumed that some overlying stratigraphic marker approximated a regionally "flat" surface (relative to paleo-sea level), then an isopach map of the interval between the upper marker and the unconformity forms a mould of the unconformity surface, where the thins represent the highs on the unconformity and the thicks define the lows. Several different intervals have previously been used to map the unconformity topography in various studies such as: the Base of Fish Scales to the unconformity (Williams, 1963), the top of Mannville Group to the unconformity (Ranger, 1984), or the top of the Wabiskaw Member to the unconformity (Flach, 1984).

Regional Paleotopography

During the Early Cretaceous (Neocomian/Aptian) in the Western Canada Sedimentary Basin, the unconformity terrane was an immature, continental, erosional landscape dominated by three major drainage systems (Ranger, 1984). These drainage systems had developed their orientations dominantly due to differential erosion of gently dipping strata. But tectonic and other structural elements certainly played a role. The subcropping strata dip to the southwest, and thus the erosional surface exposes older strata of the Middle to Upper Devonian Beaverhill Lake Group in the northeast, and strata as young as Late Jurassic toward the southwest (Leckie and Smith, 1992). Along the western edge of the basin, and underlain dominantly by Jurassic strata, a major southeast to northwest flowing trunk valley system known as the Spirit River Valley drained much of western Alberta, and at times probably much of the western United States (Ranger, 1984, 1987). The length of this system is not surprising since it lay along the axis of the incipient foreland trough of the North American Cordillera.

A central drainage valley system known as the Edmonton Channel valley system had its headwaters in the Swift Current Platform of southeastern Alberta and southwestern Saskatchewan and flowed toward the north-northwest (Williams, 1963; Ranger, 1984). The position of the mouth of the system is not well known, but it may have emptied directly into the Boreal sea to the north or may have connected with, and thus have been a tributary to, the Spirit River valley. The eastern side of the Edmonton Channel valley system was a major axial ridge system of resistant Devonian carbonates known as the Wainwright Ridge in central Alberta and the Grosmont High in northeastern Alberta.

East of this axial ridge system lay the third major drainage valley system, informally referred to here as the McMurray valley system. It is in this valley system that the Athabasca Oil Sands Deposit was localised. The valley system is confined to the northeast by the highlands of the Canadian Shield, and its axis follows a trend parallel to the strike of the outcrop of the Canadian Shield through south central Saskatchewan and Manitoba (Ranger, 1984). Somewhat younger Lower Cretaceous sediments are also known to occur as far away as western Ontario, along what would appear to be an extrapolation of the known trend of the drainage system (Try *et al.*, 1984). The paleotopographic low that forms the axis of the McMurray valley system has been localised by the dissolution of evaporitic facies mainly of the Middle Devonian Prairie Evaporite, but also to some degree the Lower Devonian Cold Lake and Lotsberg Formations. This dissolution was responsible for structural subsidence of overlying drainage basin before, during, and after deposition of the Wabiskaw/McMurray reservoir sediments. The McMurray valley system is eroded into Middle to Upper Devonian carbonates and shales of the Beaverhill Lake Group in the east and Upper Devonian carbonates of the Woodbend Group in the west.

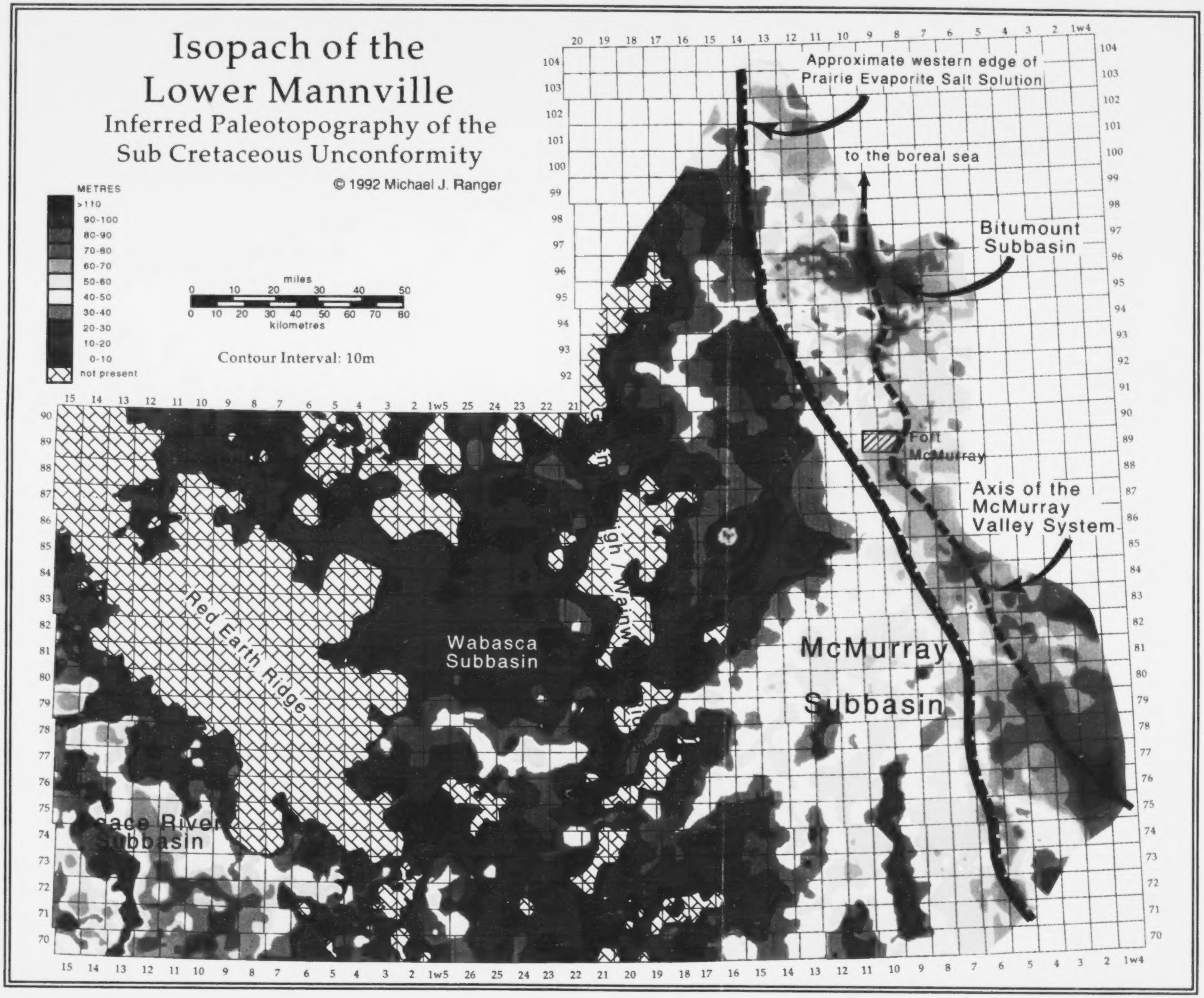
Each of these three trunk drainage systems constitute what may be thought of as depositional subbasins. Certainly this is true as far as deposition of the Lower Mannville is concerned. During the major sea-level transgressions of the Aptian and Albian, each valley system would have been flooded and would have reacted independently depending on the topography and dynamics of the sediment supply.

In the Athabasca study area, the top of the Upper Mannville Group is unsuitable as a datum due to erosion in the northeast. In this study the isopach of the McMurray Formation itself is used as a model of the unconformity paleotopography (Fig. V-1). Some thin, patchy, Aptian or Neocomian sediments known as the Deville (Badgley, 1952) or more generally, the Detrital, may lie between the McMurray Formation and the unconformity. However, known occurrences of these are rare and are not readily distinguished on geophysical well logs, which make up the bulk of the subsurface data in this study.

Paleotopography of the McMurray Subbasin

The map of the sub-Cretaceous unconformity topography underlying the Athabasca Deposit reveals a northerly-trending, axial ridge that effectively divides the area into two subbasins here termed the McMurray subbasin in the east and the Wabasca subbasin in the west (Fig. V-1). This ridge is informally known as the Grosmont High because it apparently results from resistant carbonates of the Grosmont Formation. The Grosmont High is the northerly expression of the Wainwright Ridge (Ranger, 1984). The McMurray formation is missing, and apparently was not deposited on the crest of the Grosmont High. These areas are shown in a brickwork pattern, and would have been highland areas and then islands during marine transgressions. The Wainwright Ridge - Grosmont High complex has numerous spurs branching obliquely away from it on both the east and west sides (Fig. V-1). On the west side these spurs trend in a northeast direction, and the valleys between them form major northeast flowing tributaries that can be mapped across to the eastern edge of the McMurray subbasin. They apparently feed the main valley system of the McMurray valley system. In the south-central portion of the study area is a large ridge that extends along ranges 9 and 10 from township 77 down to at least township 70. This is the extension of a major spur from the Wainwright Ridge south of the Athabasca area. To the north another major spur extends at an oblique angle to the main ridge. The intervening valley forms another major tributary of the McMurray system, but one that flows dominantly north to approximately township 94 where it abruptly turns to the east and enters the trunk system in the area just south of the Bitumont subbasin.

Figure V-1. The sub-Cretaceous unconformity surface can be modelled by mapping the thickness of a suitable interval whose base lies directly on the unconformity surface. If it is assumed that some overlying stratigraphic marker approximates a regionally "flat" surface (relative to paleo-sea level), then an isopach map of the interval between the upper marker and the unconformity forms a mould of the unconformity surface, where the thins represent the highs on the unconformity and the thicks define the lows. The isopach of the Lower Mannville is used in this study because in the northeast of the Athabasca study area, some portions of the Upper Mannville Group have been eroded.



Isopach of the Lower Mannville

Inferred Paleotopography of the Sub Cretaceous Unconformity

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METRES
>110
90-100
80-90
70-80
60-70
50-60
40-50
30-40
20-30
10-20
0-10
not present
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0 10 20 30 40 50
0 10 20 30 40 50 60 70 80
kilometres
Contour Interval: 10m
Approximate western edge of Prairie Evaporite Salt Solution
to the boreal sea
Bitumount Subbasin
Fort McMurray
Axis of the McMurray Valley System
McMurray Subbasin
Wabasca Subbasin
Red Earth Ridge
Peace River Subbasin
Wainwright High
1w4
1w5
104
70

On the west side of the Grosmont High, in the Wabasca subbasin, resistant spurs appear to be of shorter extent, but are less well defined because of poorer well control. The Wabasca subbasin contains an extension of the Athabasca Oil Sands reservoirs of the McMurray Formation and Wabiskaw Member, but it also hosts the younger Grand Rapids Oil Sand reservoirs of the Wabasca Deposit.

The sub-Cretaceous unconformity was not a peneplaned surface as many authors have suggested (Nelson and Glaister, 1978; Banerjee, 1986). This impression is simply a function of well control. Drawing a cross-section, for instance, across 300 kilometres using only approximately 50 wells will inevitably be interpreted erroneously to show an extremely subdued topography (Banerjee, 1986). In point of fact, the closer the well control, the more complex the surface appears (compare the contours at the eastern edge of the map in Fig. V-1 to the contours in the centre of the study area).

METHODS AND RESULTS

Digitised Core

One hundred and twenty six cores were examined in detail from the study area in south Athabasca. Preliminary studies and the numerous previous studies discussed above indicated that facies are very numerous and complex, and typically vary considerably over only a very short interval. Statistical methods for sedimentological analysis have been proposed in the past and have shown significant results in many studies in the past (see discussion in Ranger and Pemberton, 1991). But a search of the literature revealed no case studies where these methods were used as the prime method for the analysis and interpretation of facies. If these methods can indeed be useful in a practical study, then the complex sedimentary systems of the McMurray Formation make an ideal candidate, because this complexity has made a qualitative paleoenvironmental interpretation of the McMurray Formation a difficult and, so far, elusive enterprise.

Typically, sedimentological interpretation is a very subjective practice, and consists of classifying distinctive sedimentary units into facies, that is, intervals displaying similar physical and biogenic features. These facies are then interpreted to represent particular depositional environments, based on the sediment type, the physical and biogenic structures characteristic of the facies, and the position of the facies in the vertical succession. This approach is adequate when dealing with relatively simple sedimentary packages. For the large quantity of complex and highly variable sedimentological data observed in the McMurray Formation, identifying and classifying facies by eye is formidable and liable to be fraught with subjective error. An objective statistical approach seems more appropriate.

Using a microcomputer in the core examination lab, all the sedimentological data from the cores were collected directly in digital form. Facies were recorded as intervals identified by a combination of codes representing lithology, grain size, and the simple presence or absence of specific physical sedimentary structures, lithological accessories and ichnofossils. The method demonstrated by Ranger and Pemberton (1991) for ichnofacies analysis was used for the McMurray analysis, with minor modifications.

Statistical Facies Analyses

Ranger and Pemberton (1991) adopted and refined a two-phased, semi-parametric statistical technique in their facies analysis. (It is considered semi-parametric because, although the techniques themselves are non-parametric, the search for outliers and tests of significance, as well as other subsidiary tests, do assume the presence of normally distributed statistics.)

The technique first classifies measured stratigraphic intervals into groups (i.e. facies) using similarity analysis, also known as cluster analysis. Then significant "preferred" vertical associations are determined using Markov transition analysis to produce an idealised model for the vertical ichnofaunal succession. This technique is not limited to ichnofossil analyses of course, and indeed has its foundations in facies analysis using physical characteristics of stratigraphic intervals (Harbaugh and Bonham-Carter, 1970). In the facies analysis of the McMurray Formation, observations of both biogenic and physical features are given equal weight in the description of facies.

Cluster Analysis

Ranger and Pemberton (1991) describe in detail the cluster analysis technique for differentiating stratigraphic intervals into facies classes based on physical and biogenic observations. They also conducted empirical trials to see which of several, common, clustering algorithms is the most suitable for stratigraphic analyses. Only a brief overview of the technique is described here.

Cluster analysis is a technique for grouping samples or entities into discrete classes based on recurrent common attributes. The first step in a cluster analysis is to calculate a matrix of similarity coefficients. Between all possible pairs of entities, a coefficient is calculated that represents their distance apart in multidimensional space. If the attributes are continuous data (rather than binary), then the set of attribute values are an entity's coordinates in this multidimensional space. For binary data however, this "distance" coefficient is the result of some simple function based on the presence or absence of the attributes. Ranger and Pemberton (1991) used what is known as Euclidian distance, which gives equal weight to the mutual absence of attributes. In the present study, the presence or absence of up to forty-nine different attributes was recorded. For all of the interval samples, the "absent" attributes far outnumbered those present. It was considered more appropriate to give more significance to the presence of attributes rather than to base the analysis on data that would otherwise be biased toward "absent" attributes. A version of the "Jaccard" coefficient, modified to measure dissimilarity (distance) rather than similarity was therefore used in this study. The Jaccard coefficient has been judged to give superior results, on a par with the Euclidian distance method, in empirical trials (Ranger and Pemberton, 1991), but was downgraded because of the possibility of encountering division by zero in the case where all attributes are absent in both of the samples. Although barren intervals may be common in ichnofaunal analysis, none was encountered in this study.

The next step in cluster analysis is the fusion of the two entities that have the greatest similarity into a single cluster. The similarity coefficients are then recalculated based on some transformation function that combines the similarity coefficients of the fused entities. The fusion of entities or clusters of entities is continued until all entities reside in a single cluster. The transformation function used in this study is known as the Error Sum of Squares, which, for each iteration, fuses the two clusters of observations that yield the least increase in the Euclidian sum of squares of the distances of each observation to the centroid of the combined cluster. This method was also judged superior for use with sedimentological data (Ranger and Pemberton, 1991).

The modification of the Jaccard function to reflect dissimilarity rather than similarity was adopted in order to utilise the Error Sum of Squares transformation function for clustering, which requires a matrix of dissimilarity coefficients as starting input. Between any two entities, the normal Jaccard coefficient of similarity is expressed by the function:

$$\mathrm{Coeff}_d = \frac{A}{A+B+C}$$

where A is the number of attributes present in both observations, B is the number of attributes present in the first observation but absent in the second, and C is the number of attributes present in the second observation but absent in the first. To measure dissimilarity, the function is the complement of the normal Jaccard coefficient:

$$\mathrm{Coeff}_d = \frac{B+C}{A+B+C}$$

Cluster Analysis Results

Three separate cluster analyses were performed, one each for the sand dominant facies, the shale dominant facies, and the interbedded facies. Complex statistical analysis is not required to reach the obvious conclusion that these three groups represent a basic first order classification, weighted in a sense on hydrodynamic conditions. This initial subdivision also breaks down the number of entities (facies intervals) for each analysis into manageable numbers. The number of entities can be a concern, since it should be remembered that the initial matrix of similarity coefficients means that every entity must be compared to all others. This requires a number of iterations that grows exponentially with the number of entities: $x^2/2$, where x is the number of entities.

The resulting cluster scheme is typically displayed as a dendrogram, which displays the hierarchy of similarity relationships. While instructive to examine in the analysis process, the dendrogram itself is not the purpose of the technique. The ultimate result is to identify as "similar" all entities residing in each cluster; similarity being defined by the similarity function. These clusters can then be considered the derived facies.

Major clusters represent an objective classification of the observed sedimentary units into discrete facies.

Cluster Analysis Interpretation

The cluster analyses resulted in the differentiation of 21 facies: 9 interbedded, 6 sandy and 6 shaly. The derived facies are best described by, and interpreted from, a graphic display (Figs. V-2, V-3, V-4) showing the mean facies thickness, dominant sand grain size, dominant bedding thickness of interbedded units and the characteristic physical structures, as well as mean diversity of trace fossil forms, relative abundance of ichnogenera, and relative intensity of bioturbation. Core photographs of intervals that were classified into the same facies (Figs. V-5, V-6, V-7, V-8) attest to the efficacy of the technique and the legitimacy of the results. The facies interpretation is based on the sedimentology, physical structures and ichnology, as well as position within the facies succession. Some of the facies successions are complex and the second step in the numerical analysis, Markov analysis, proved invaluable in unravelling the facies relationships.

Markov Analysis

Ranger and Pemberton (1991) give a detailed review of the Markov analysis technique used for examining stratigraphic successions in the subsurface, and also point out the potential pitfalls of using the method for analysis of repeated observations over the same stratigraphic interval (i.e. multiple boreholes). Again only a brief overview is presented here, and the

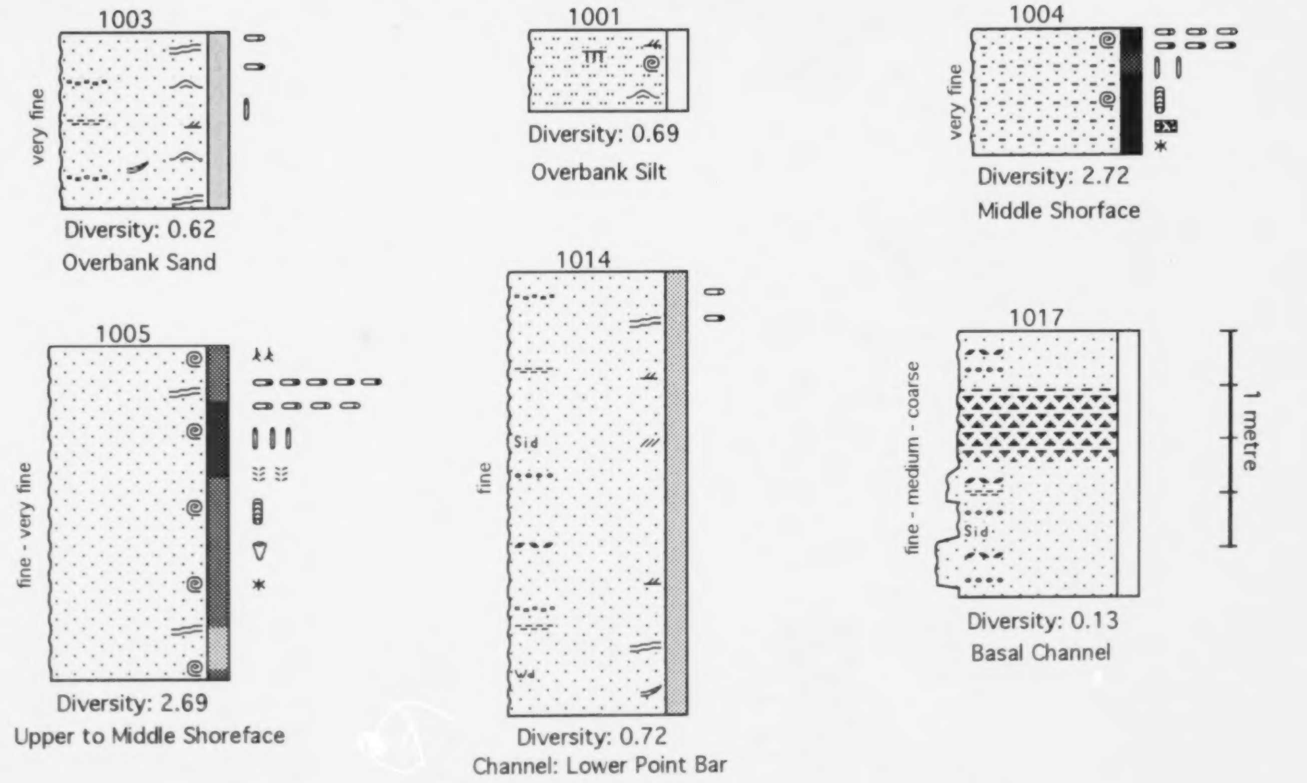

1003
very fine
Diversity: 0.62
Overbank Sand
1001
Diversity: 0.69
Overbank Silt
1004
very fine
Diversity: 2.72
Middle Shorface
1005
fine - very fine
Diversity: 2.69
Upper to Middle Shoreface
1014
fine
Sid
Diversity: 0.72
Channel: Lower Point Bar
1017
fine - medium - coarse
Sid
Diversity: 0.13
Basal Channel
1 metre

Figure V-2. Sandy facies determined from cluster analysis. Relative length is scaled to the mean thickness. Diversity is the mean number of ichnofossil forms observed in all intervals assigned to the facies. Facies numbers are arbitrarily assigned for identification purposes only. Shaded bar at the right of the column is relative bioturbation intensity. For legend see figure V-15.

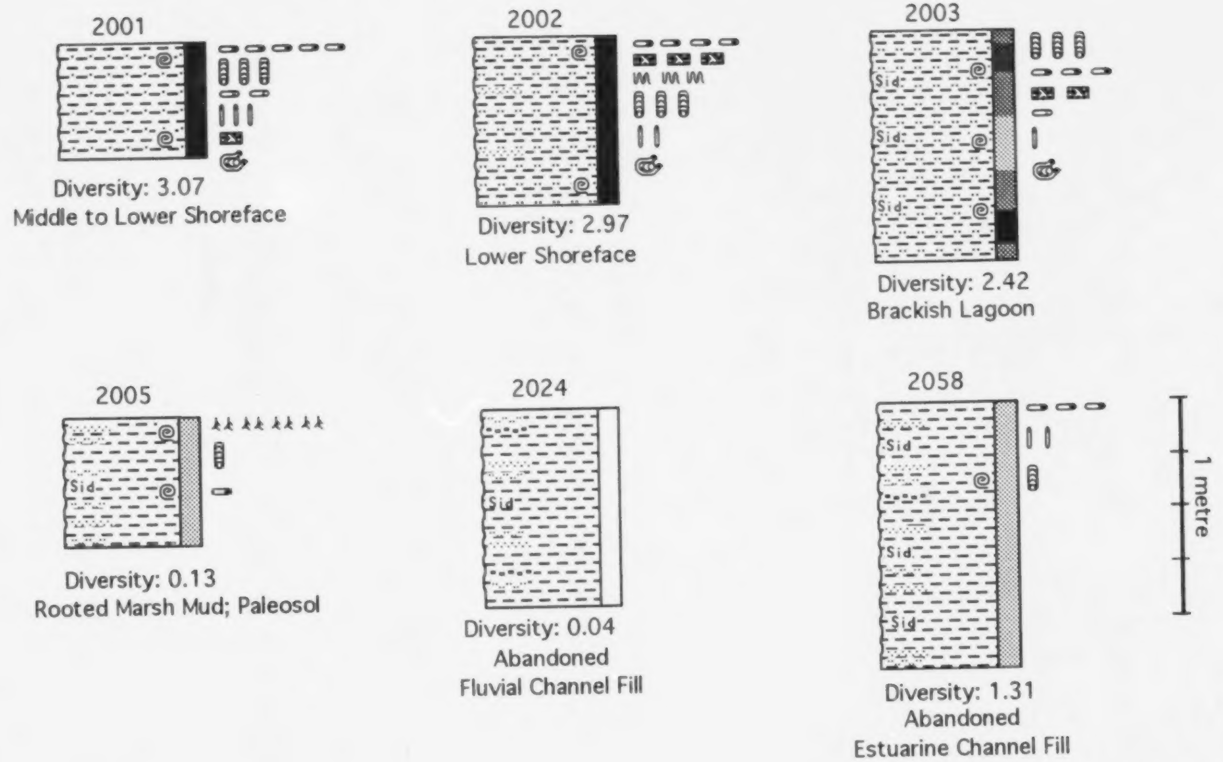

2001
Diversity: 3.07
Middle to Lower Shoreface
2002
Diversity: 2.97
Lower Shoreface
2003
Sid
Diversity: 2.42
Brackish Lagoon
2005
Sid
Diversity: 0.13
Rooted Marsh Mud; Paleosol
2024
Sid
Diversity: 0.04
Abandoned
Fluvial Channel Fill
2058
Sid
Diversity: 1.31
Abandoned
Estuarine Channel Fill
1 metre

Figure V-3. Muddy facies determined from cluster analysis. Relative length is scaled to the mean thickness. Diversity is the mean number of ichnofossil forms observed in all intervals assigned to the facies. Facies numbers are arbitrarily assigned for identification purposes only. Shaded bar at the right of the column is relative bioturbation intensity. For legend see figure V-15.

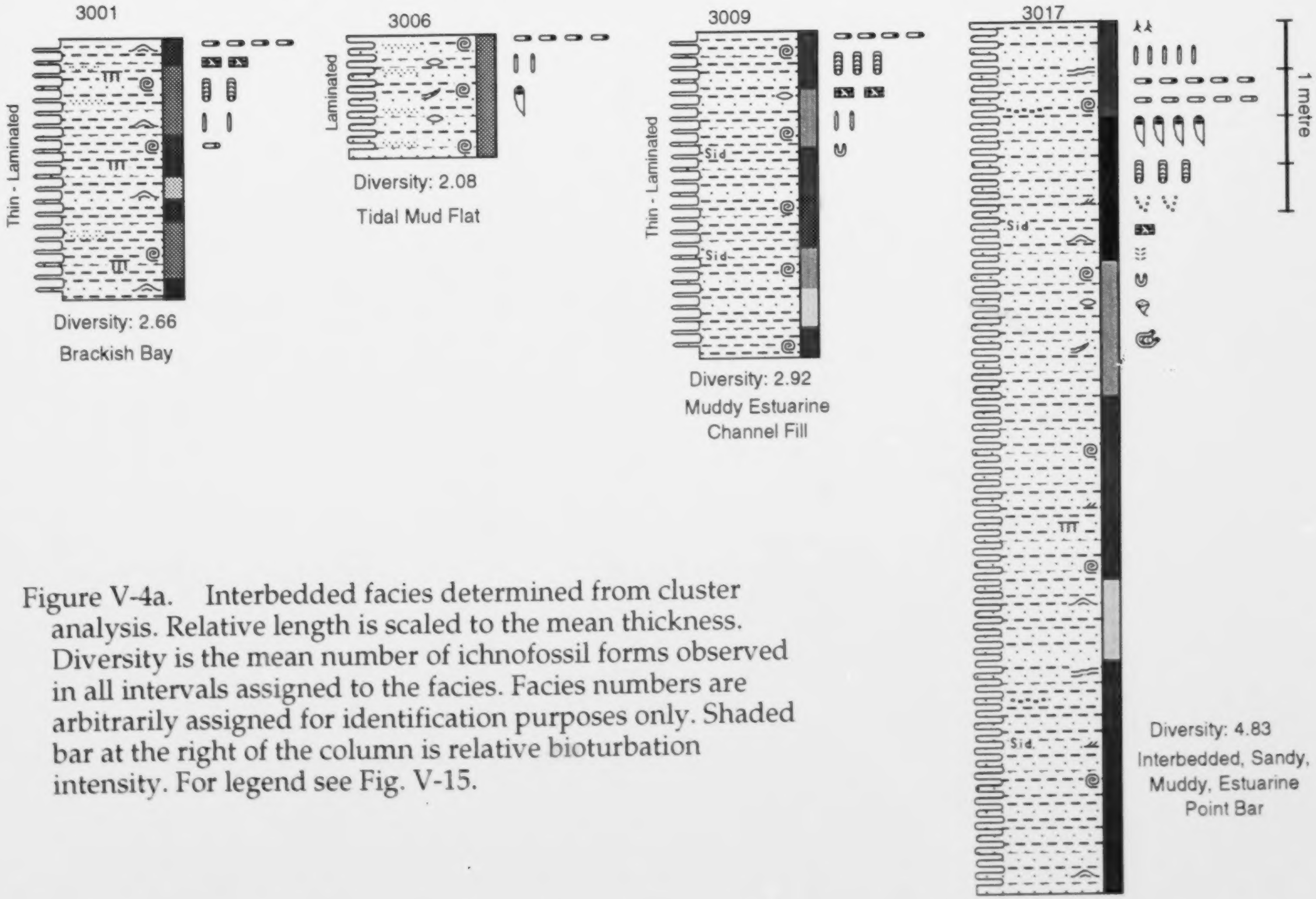

3001
Thin - Laminated
Diversity: 2.66
Brackish Bay
3006
Laminated
Diversity: 2.08
Tidal Mud Flat
3009
Thin - Laminated
Sid
Sid
Diversity: 2.92
Muddy Estuarine
Channel Fill
3017
Sid
Sid.
1 metre
Diversity: 4.83
Interbedded, Sandy,
Muddy, Estuarine
Point Bar

Figure V-4a. Interbedded facies determined from cluster analysis. Relative length is scaled to the mean thickness. Diversity is the mean number of ichnofossil forms observed in all intervals assigned to the facies. Facies numbers are arbitrarily assigned for identification purposes only. Shaded bar at the right of the column is relative bioturbation intensity. For legend see Fig. V-15.

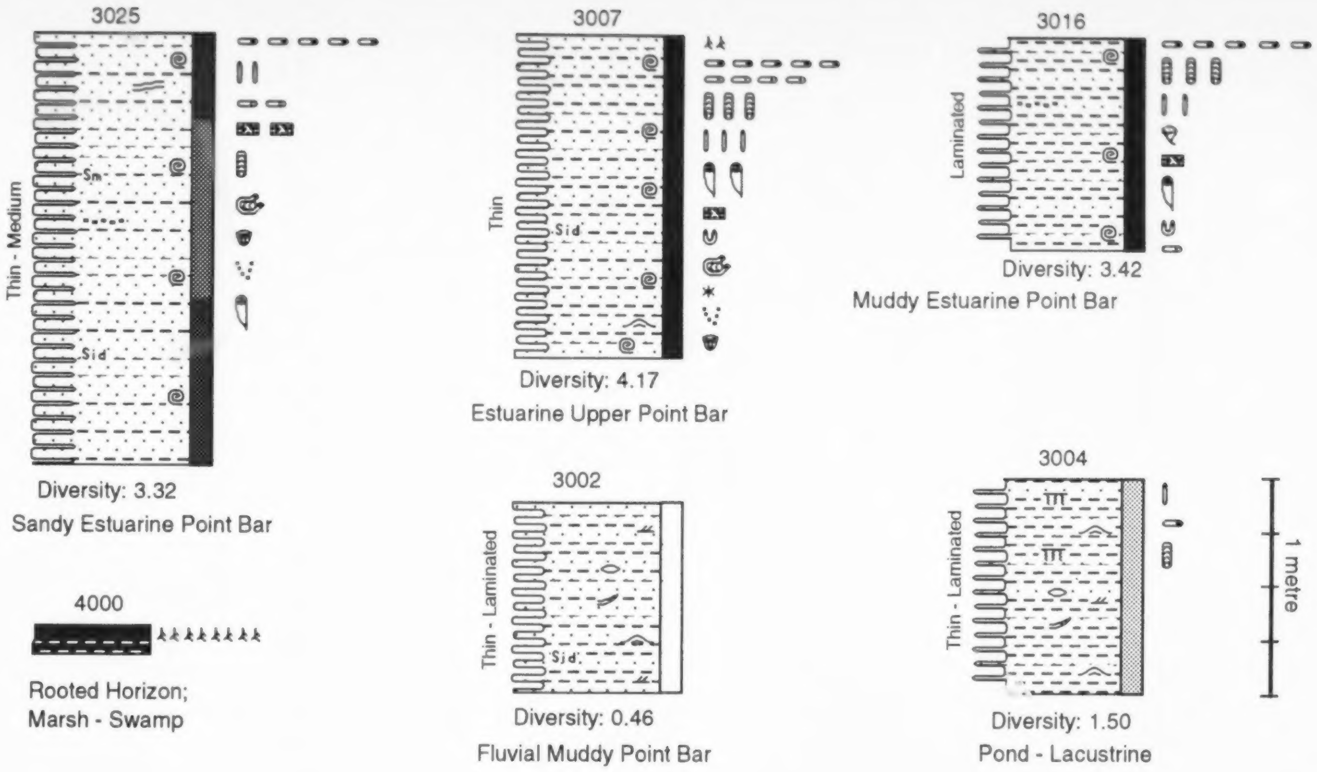

3025
Thin - Medium
Sm
Sid
Diversity: 3.32
Sandy Estuarine Point Bar
4000
Rooted Horizon;
Marsh - Swamp
3007
Thin
Sid
Diversity: 4.17
Estuarine Upper Point Bar
3016
Laminated
Diversity: 3.42
Muddy Estuarine Point Bar
3002
Thin - Laminated
Sid
Diversity: 0.46
Fluvial Muddy Point Bar
3004
Thin - Laminated
Diversity: 1.50
Pond - Lacustrine
1 metre

Figure V-4b. Interbedded facies determined from cluster analysis. Relative length is scaled to the mean thickness. Diversity is the mean number of ichnofossil forms observed in all intervals assigned to the facies. Facies numbers are arbitrarily assigned for identification purposes only. Shaded bar at the right of the column is relative bioturbation intensity. For legend see fig. V-15.

Figure V-5. Examples of core intervals classified as belonging to the same facies through cluster analysis. Facies type 3017 – interpreted as interbedded, sandy, muddy, estuarine point bar.

A. 10-8-73-8W4 (526.0 m).
B. 7-18-76-5W4 (354.8 m).
C. 11-32-73-6W4 (443.8 m).
D. 7-18-76-5W4 (340.0 m).

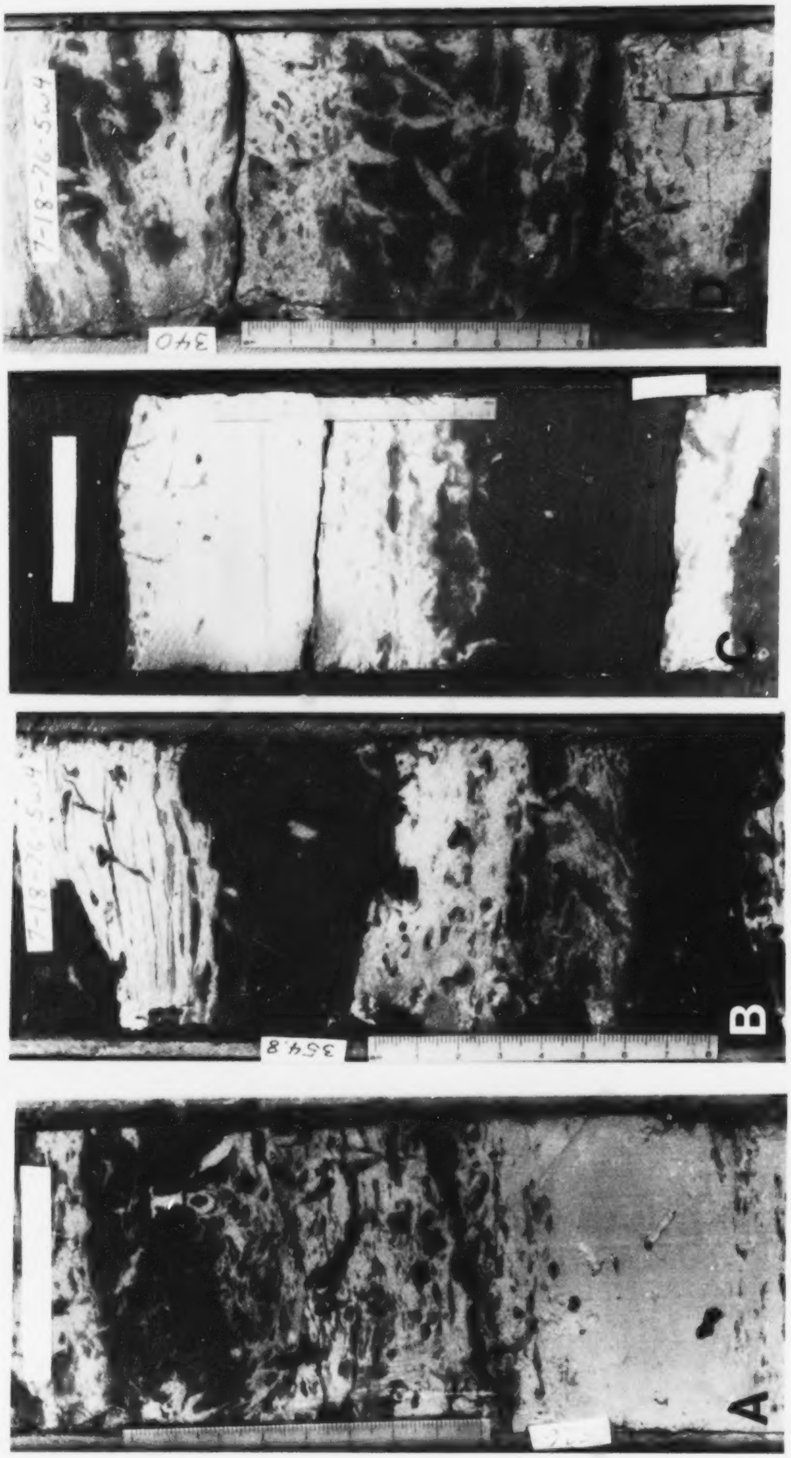
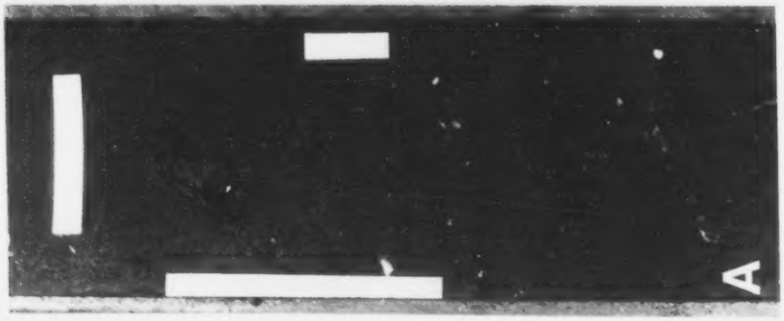
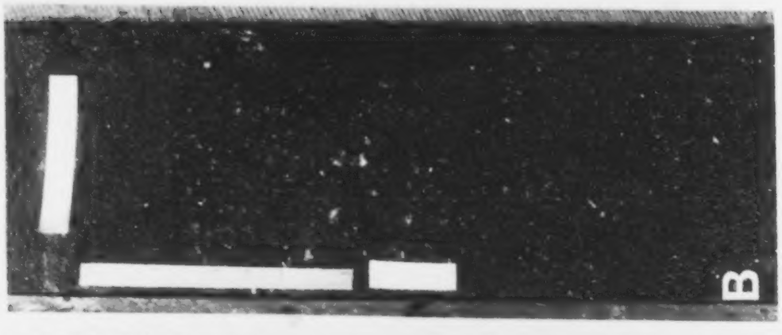
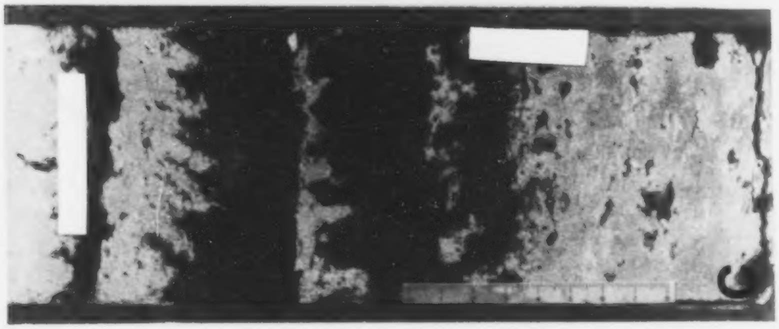

7-18-76-5W4
340
D
C
7-18-76-5W4
354.8
B
A

Figure V-6. Examples of core intervals classified as belonging to the same facies through cluster analysis. Facies type 1014 (A and B) - interpreted as lower fluvial point bar. Facies type 3025 (C and D) – interpreted as sandy estuarine point bar.

A. 10-29-73-5W4 (474.1 m).
B. 10-29-73-5W4 (476.2 m).
C. 10-29-73-5W4 (447.0 m).
D. 6-8-73-6W4 (496.4 m).


A


B


C

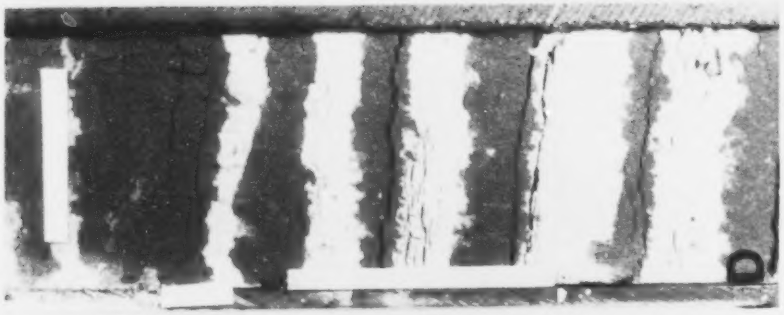

D

Figure V-7. Examples of core intervals classified as belonging to the same facies through cluster analysis. Facies type 2002 – interpreted as lower shoreface.

A. 11-32-73-6W4 (445.0 m).
B. 11-26-72-8W4 (504.3 m).
C. 7-3-73-6W4 (513.4 m).
D. 8-29-77-10W4 (438.1 m).

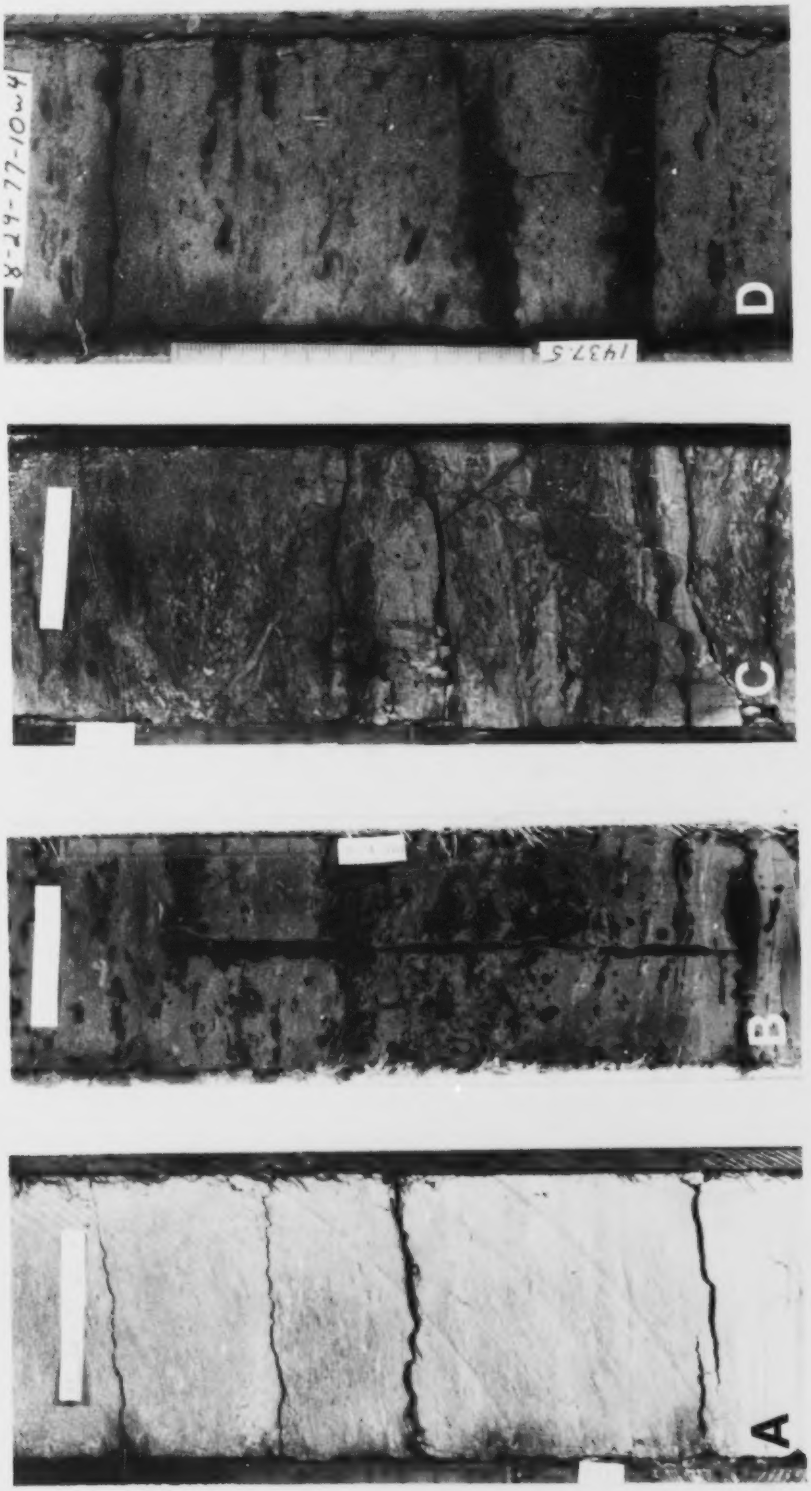
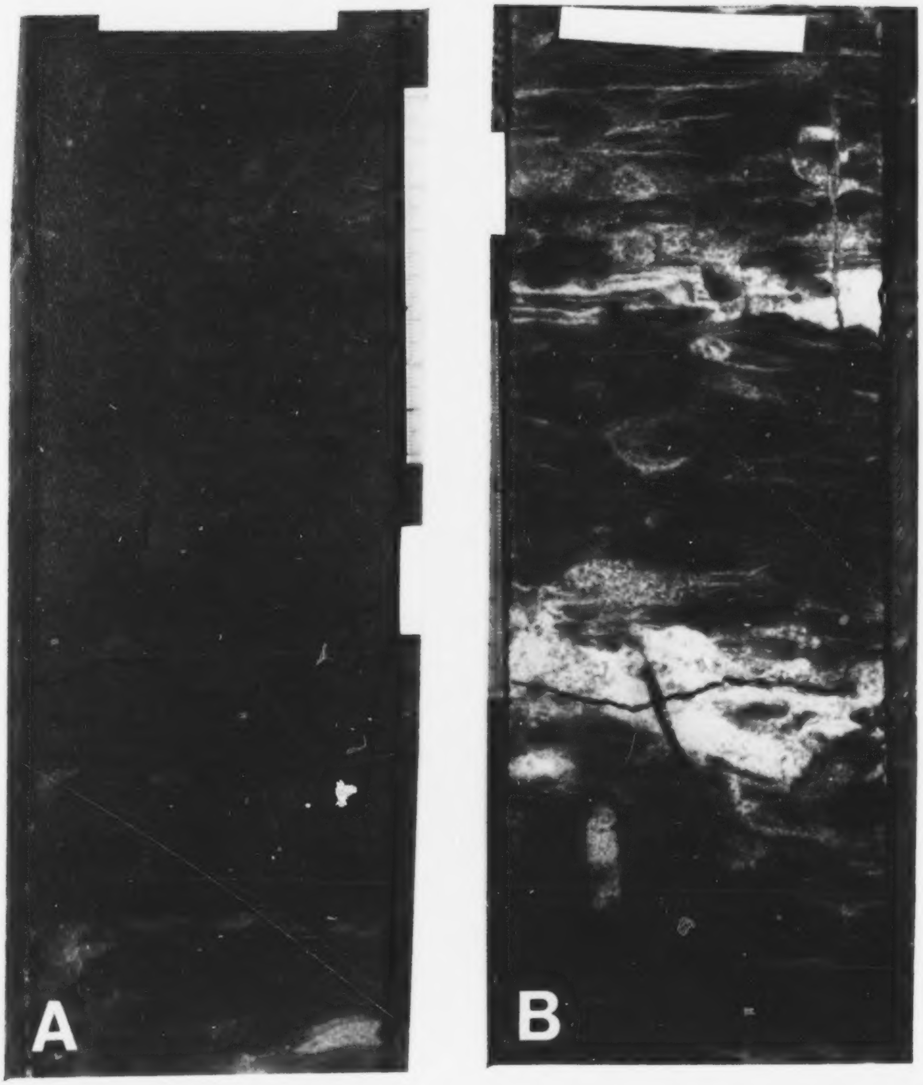

8-29-77-10w4
1437.5
D
C
B
A

Figure V-8. Examples of core intervals classified as belonging to the same facies through cluster analysis. Facies type 1004 - interpreted as middle shoreface sand.

A. 6-8-73-6W4 (484.9 m).
B. 6-8-73-6W4 (489.7 m).


A
B

technique used in this study is essentially the same as that recommended by Ranger and Pemberton (1991).

Markov analysis measures the probability of transition from one facies to another in a vertical succession of sedimentary intervals. A Markov property or process is one in which the probability of a process being in a given facies at a particular point in time may be deduced from knowledge of the immediately preceding facies. In the variation of the technique most commonly used for stratigraphic studies, the frequency of upward transitions from one facies to another in a vertical sequence is tabulated in a matrix table (Table V-1, V-2). Each cell contains the frequency of transitions from the facies states denoted by the rows of the matrix to the facies state denoted by the columns of the matrix. Transitions from one facies state to the same facies state are considered unobservable or undefined and therefore these cells, which make up the principal diagonal of the matrix, are constrained to zeros. In this study the input matrix of transition frequencies was tallied using the facies assigned to the logged intervals by the cluster analyses. Two additional facies were added to the 21 resulting from the cluster analyses. These are actually significant horizons, rather than facies: major erosional scour surfaces (as suggested by Cant and Walker, 1976); and rooted horizons including thin coals and organic black shales were also included as a significant facies state (as suggested by Ranger and Pemberton, 1991).

The next step in Markov analysis is to calculate a matrix of "expected" transition frequencies, which provides a model of randomness or independence, i.e. the absence of the Markov property in the data sequence (Table V-3). The expected transition frequencies are then subtracted from the observed transition frequencies, yielding a matrix of differences, termed the "residuals" (Table V-4). Large residuals can be considered outliers and therefore non-random

One can test for outliers by first standardising them to a mean of 0.0 and a standard deviation of 1.0. Then, assuming that the residuals are normally distributed, standard two-tailed tests can be applied, whereby 90% of the residuals should lie within ±1.6 standard deviations of the mean, approximately 95% should lie within ±2 standard deviations, and approximately 99.5% should lie within ±3 standard deviations (Table V-5).

Table V-1. TRANSITION FREQUENCY MATRIX

FACIES	2001	3001	5000	1001	2002	2003	3002	4000	2005	1003	3004	1004	1005	3006	3007	3009	1014	1017	2024	3016	3017	3025	2058	ROW TOTAL
2001		0	2	0	9	5	1	14	1	0	1	14	6	0	4	2	3	0	0	2	2	0	1	67
3001	2		0	1	7	10	0	1	0	11	0	2	6	2	2	1	0	0	0	1	1	0	4	51
5000	0	2		0	2	0	0	0	0	1	1	1	2	0	1	0	2	3	0	0	0	1	2	18
1001	0	1	1		3	4	1	3	0	3	1	1	2	0	1	0	1	0	2	1	0	2	0	27
2002	18	7	1	5		11	1	11	1	3	3	11	5	2	14	4	2	0	1	4	6	1	1	112
2003	5	5	3	4	10		1	55	3	9	1	8	7	3	12	12	11	1	4	4	8	3	4	173
3002	0	0	0	0	0	2		2	1	4	0	1	2	2	0	0	8	2	3	1	1	1	4	34
4000	10	5	2	3	24	29	5		27	6	2	15	14	3	19	7	8	1	7	8	13	7	2	217
2005	4	1	0	0	3	0	0	57		2	1	0	0	0	0	1	3	1	0	0	1	0	0	74
1003	0	9	0	1	4	10	4	2	4		5	3	3	6	9	5	0	0	1	3	3	3	3	78
3004	1	4	0	0	2	2	1	0	0	7		0	0	2	2	0	4	0	3	0	0	0	5	33
1004	6	2	0	3	12	12	0	7	3	5	0		15	1	4	1	3	0	2	1	0	0	1	78
1005	10	5	0	0	9	17	2	13	4	1	1	8		5	13	4	1	1	1	4	6	11	2	118
3006	0	1	1	0	1	5	1	1	1	4	0	1	4		2	2	4	2	2	0	0	2	2	36
3007	2	1	0	3	7	16	1	19	6	7	1	8	15	1		1	7	0	0	1	1	2	0	99
3009	2	3	1	3	3	7	0	3	0	3	5	0	6	2	2		5	1	3	0	1	0	2	52
1014	1	2	0	1	3	13	7	2	1	0	4	2	2	3	9	4		15	11	2	11	16	4	113
1017	0	0	2	0	0	4	3	1	1	1	1	0	1	0	0	0	12		5	0	1	2	0	34
2024	0	4	3	3	1	3	3	5	4	2	8	0	2	0	2	0	6	5		1	1	1	3	57
3016	2	0	0	0	5	5	0	10	0	0	0	1	6	0	0	0	0	0	1		1	1	0	32
3017	1	1	0	0	4	8	0	12	2	9	0	0	8	1	2	2	7	1	5	1		0	2	66
3025	1	0	1	0	2	7	2	1	3	5	0	0	10	0	1	3	8	2	3	0	2		0	51
2058	1	1	1	1	1	3	1	7	4	2	4	2	0	1	0	4	4	1	2	0	4	1		45
TOTAL	66	54	18	28	112	173	34	226	66	85	39	78	116	34	99	53	99	36	56	34	63	54	42	1665

Table V-2. OBSERVED TRANSITION PROBABILITY MATRIX

FACIES	2001	3001	5000	1001	2002	2003	3002	4000	2005	1003	3004	1004	1005	3006	3007	3009	1014	1017	2024	3016	3017	3025	2058
2001		0.0000	0.0299	0.0000	0.1343	0.0746	0.0149	0.2090	0.0149	0.0000	0.0149	0.2090	0.0896	0.0000	0.0597	0.0299	0.0448	0.0000	0.0000	0.0299	0.0299	0.0000	0.0149
3001	0.0392		0.0000	0.0196	0.1373	0.1961	0.0000	0.0196	0.0000	0.2157	0.0000	0.0392	0.1176	0.0392	0.0392	0.0196	0.0000	0.0000	0.0000	0.0196	0.0196	0.0000	0.0784
5000	0.0000	0.1111		0.0000	0.1111	0.0000	0.0000	0.0000	0.0000	0.0556	0.0556	0.0556	0.1111	0.0000	0.0556	0.0000	0.1111	0.1667	0.0000	0.0000	0.0000	0.0556	0.1111
1001	0.0000	0.0370	0.0370		0.1111	0.1481	0.0370	0.1111	0.0000	0.1111	0.0370	0.0370	0.0741	0.0000	0.0370	0.0000	0.0370	0.0000	0.0741	0.0370	0.0000	0.0741	0.0000
2002	0.1607	0.0625	0.0089	0.0446		0.0982	0.0089	0.0982	0.0089	0.0268	0.0268	0.0982	0.0446	0.0179	0.1250	0.0357	0.0179	0.0000	0.0089	0.0357	0.0536	0.0089	0.0089
2003	0.0289	0.0289	0.0173	0.0231	0.0578		0.0058	0.3179	0.0173	0.0520	0.0058	0.0462	0.0405	0.0173	0.0694	0.0694	0.0636	0.0058	0.0231	0.0231	0.0462	0.0173	0.0231
3002	0.0000	0.0000	0.0000	0.0000	0.0000	0.0588		0.0588	0.0294	0.1176	0.0000	0.0294	0.0588	0.0588	0.0000	0.0000	0.2353	0.0588	0.0882	0.0294	0.0294	0.0294	0.1176
4000	0.0461	0.0230	0.0092	0.0138	0.1106	0.1336	0.0230		0.1244	0.0276	0.0092	0.0691	0.0645	0.0138	0.0876	0.0323	0.0369	0.0046	0.0323	0.0369	0.0599	0.0323	0.0092
2005	0.0541	0.0135	0.0000	0.0000	0.0405	0.0000	0.0000	0.7703		0.0270	0.0135	0.0000	0.0000	0.0000	0.0000	0.0135	0.0405	0.0135	0.0000	0.0000	0.0135	0.0000	0.0000
1003	0.0000	0.1154	0.0000	0.0128	0.0513	0.1282	0.0513	0.0256	0.0513		0.0641	0.0385	0.0385	0.0769	0.1154	0.0641	0.0000	0.0000	0.0128	0.0385	0.0385	0.0385	0.0385
3004	0.0303	0.1212	0.0000	0.0000	0.0606	0.0606	0.0303	0.0000	0.0000	0.2121		0.0000	0.0000	0.0606	0.0606	0.0000	0.1212	0.0000	0.0909	0.0000	0.0000	0.0000	0.1515
1004	0.0769	0.0256	0.0000	0.0385	0.1538	0.1538	0.0000	0.0897	0.0385	0.0641	0.0000		0.1923	0.0128	0.0513	0.0128	0.0385	0.0000	0.0256	0.0128	0.0000	0.0000	0.0128
1005	0.0847	0.0424	0.0000	0.0000	0.0763	0.1441	0.0169	0.1102	0.0339	0.0085	0.0085	0.0678		0.0424	0.1102	0.0339	0.0085	0.0085	0.0085	0.0339	0.0508	0.0932	0.0169
3006	0.0000	0.0278	0.0278	0.0000	0.0278	0.1389	0.0278	0.0278	0.0278	0.1111	0.0000	0.0278	0.1111		0.0556	0.0556	0.1111	0.0556	0.0556	0.0000	0.0000	0.0556	0.0556
3007	0.0202	0.0101	0.0000	0.0303	0.0707	0.1616	0.0101	0.1919	0.0606	0.0707	0.0101	0.0808	0.1515	0.0101		0.0101	0.0707	0.0000	0.0000	0.0101	0.0101	0.0202	0.0000
3009	0.0385	0.0577	0.0192	0.0577	0.0577	0.1346	0.0000	0.0577	0.0000	0.0577	0.0962	0.0000	0.1154	0.0385	0.0385		0.0962	0.0192	0.0577	0.0000	0.0192	0.0000	0.0385
1014	0.0088	0.0177	0.0000	0.0088	0.0265	0.1150	0.0619	0.0177	0.0088	0.0000	0.0354	0.0177	0.0177	0.0265	0.0796	0.0354		0.1327	0.0973	0.0177	0.0973	0.1416	0.0354
1017	0.0000	0.0000	0.0588	0.0000	0.0000	0.1176	0.0882	0.0294	0.0294	0.0294	0.0294	0.0000	0.0294	0.0000	0.0000	0.0000	0.3529		0.1471	0.0000	0.0294	0.0588	0.0000
2024	0.0000	0.0702	0.0526	0.0526	0.0175	0.0526	0.0526	0.0877	0.0702	0.0351	0.1404	0.0000	0.0351	0.0000	0.0351	0.0000	0.1053	0.0877		0.0175	0.0175	0.0175	0.0526
3016	0.0625	0.0000	0.0000	0.0000	0.1562	0.1562	0.0000	0.3125	0.0000	0.0000	0.0000	0.0312	0.1875	0.0000	0.0000	0.0000	0.0000	0.0000	0.0312		0.0312	0.0312	0.0000
3017	0.0152	0.0152	0.0000	0.0000	0.0606	0.1212	0.0000	0.1818	0.0303	0.1364	0.0000	0.0000	0.1212	0.0152	0.0303	0.0303	0.1061	0.0152	0.0758	0.0152		0.0000	0.0303
3025	0.0196	0.0000	0.0196	0.0000	0.0392	0.1373	0.0392	0.0196	0.0588	0.0980	0.0000	0.0000	0.1961	0.0000	0.0196	0.0588	0.1569	0.0392	0.0588	0.0000	0.0392		0.0000
2058	0.0222	0.0222	0.0222	0.0222	0.0222	0.0667	0.0222	0.1556	0.0889	0.0444	0.0889	0.0444	0.0000	0.0222	0.0000	0.0889	0.0889	0.0222	0.0444	0.0000	0.0889	0.0222	

ITERATIVE PROPORTIONAL FITTING METHOD WITH TÜRK`S NORMALIZED RESIDUALS

Table V-3. IPF EXPECTED (RANDOM) TRANSITION FREQUENCY MATRIX

FACIES	2001	3001	5000	1001	2002	2003	3002	4000	2005	1003	3004	1004	1005	3006	3007	3009	1014	1017	2024	3016	3017	3025	2058
2001		2.18	0.71	1.11	4.70	7.59	1.36	10.31	2.70	3.48	1.55	3.20	4.88	1.36	4.11	2.14	4.15	1.44	2.26	1.35	2.56	2.18	1.69
3001	2.03		0.54	0.84	3.55	5.73	1.02	7.79	2.04	2.63	1.17	2.41	3.69	1.03	3.11	1.61	3.14	1.08	1.71	1.02	1.94	1.64	1.27
5000	0.70	0.57		0.29	1.23	1.98	0.35	2.69	0.70	0.91	0.41	0.83	1.27	0.35	1.07	0.56	1.08	0.37	0.59	0.35	0.67	0.57	0.44
1001	1.06	0.86	0.28		1.85	2.99	0.53	4.06	1.06	1.37	0.61	1.26	1.92	0.53	1.62	0.84	1.63	0.57	0.89	0.53	1.01	0.86	0.66
2002	4.63	3.75	1.23	1.92		13.08	2.34	17.77	4.65	6.00	2.68	5.51	8.42	2.34	7.09	3.68	7.15	2.47	3.90	2.33	4.41	3.75	2.91
2003	7.48	6.06	1.98	3.10	13.08		3.78	28.72	7.51	9.71	4.33	8.91	13.60	3.78	11.46	5.95	11.56	4.00	6.31	3.77	7.14	6.06	4.70
3002	1.34	1.08	0.35	0.55	2.34	3.78		5.13	1.34	1.73	0.77	1.59	2.43	0.68	2.05	1.06	2.07	0.71	1.13	0.67	1.27	1.08	0.84
4000	9.81	7.95	2.60	4.06	17.16	27.74	4.95		9.86	12.73	5.68	11.68	17.85	4.96	15.03	7.81	15.17	5.25	8.28	4.95	9.36	7.95	6.16
2005	2.97	2.40	0.79	1.23	5.19	8.39	1.50	11.39		3.85	1.72	3.53	5.39	1.50	4.54	2.36	4.59	1.59	2.50	1.50	2.83	2.40	1.86
1003	3.16	2.56	0.84	1.31	5.53	8.94	1.60	12.15	3.18		1.83	3.77	5.75	1.60	4.85	2.52	4.89	1.69	2.67	1.60	3.02	2.56	1.99
3004	1.30	1.05	0.34	0.54	2.27	3.68	0.66	4.99	1.31	1.69		1.55	2.37	0.66	1.99	1.03	2.01	0.70	1.10	0.66	1.24	1.05	0.82
1004	3.15	2.55	0.83	1.30	5.51	8.91	1.59	12.09	3.16	4.09	1.82		5.73	1.59	4.83	2.51	4.87	1.68	2.66	1.59	3.01	2.55	1.98
1005	4.89	3.96	1.29	2.02	8.55	13.82	2.47	18.77	4.91	6.34	2.83	5.82		2.47	7.49	3.89	7.56	2.61	4.12	2.47	4.66	3.96	3.07
3006	1.41	1.15	0.37	0.59	2.47	4.00	0.71	5.43	1.42	1.84	0.82	1.68	2.57		2.17	1.13	2.19	0.76	1.19	0.71	1.35	1.15	0.89
3007	4.05	3.28	1.07	1.68	7.09	11.46	2.05	15.57	4.07	5.26	2.35	4.83	7.37	2.05		3.23	6.27	2.17	3.42	2.04	3.87	3.28	2.55
3009	2.07	1.67	0.55	0.86	3.61	5.84	1.04	7.94	2.08	2.69	1.20	2.46	3.76	1.04	3.17		3.20	1.11	1.74	1.04	1.97	1.67	1.30
1014	4.63	3.75	1.23	1.92	8.10	13.09	2.34	17.78	4.65	6.01	2.68	5.51	8.42	2.34	7.09	3.68		2.48	3.90	2.33	4.42	3.75	2.91
1017	1.34	1.08	0.35	0.55	2.34	3.78	0.68	5.14	1.34	1.74	0.77	1.59	2.43	0.68	2.05	1.06	2.07		1.13	0.67	1.28	1.08	0.84
2024	2.27	1.84	0.60	0.94	3.97	6.42	1.15	8.72	2.28	2.95	1.31	2.70	4.13	1.15	3.48	1.81	3.51	1.21		1.14	2.17	1.84	1.43
3016	1.26	1.02	0.33	0.52	2.20	3.55	0.63	4.83	1.26	1.63	0.73	1.50	2.29	0.64	1.93	1.00	1.94	0.67	1.06		1.20	1.02	0.79
3017	2.64	2.14	0.70	1.09	4.62	7.46	1.33	10.14	2.65	3.43	1.53	3.14	4.80	1.33	4.04	2.10	4.08	1.41	2.23	1.33		2.14	1.66
3025	2.03	1.64	0.54	0.84	3.55	5.73	1.02	7.79	2.04	2.63	1.17	2.41	3.69	1.03	3.11	1.61	3.14	1.08	1.71	1.02	1.94		1.27
2058	1.78	1.44	0.47	0.74	3.11	5.02	0.90	6.82	1.78	2.31	1.03	2.12	3.23	0.90	2.72	1.41	2.75	0.95	1.50	0.90	1.70	1.44	

4 iterations needed for convergence to 0.1%

Table V-4. OBSERVED MINUS IPF EXPECTED TRANSITION FREQUENCIES

FACIES	2001	3001	5000	1001	2002	2003	3002	4000	2005	1003	3004	1004	1005	3006	3007	3009	1014	1017	2024	3016	3017	3025	2058
2001		-2.18	1.29	-1.11	4.30	-2.59	-0.36	3.69	-1.70	-3.48	-0.55	10.80	1.12	-1.36	-0.11	-0.14	-1.15	-1.44	-2.26	0.65	-0.56	-2.18	-0.69
3001	-0.03		-0.54	0.16	3.45	4.27	-1.02	-6.79	-2.04	8.37	-1.17	-0.41	2.31	0.97	-1.11	-0.61	-3.14	-1.08	-1.71	-0.02	-0.94	-1.64	2.73
5000	-0.70	1.43		-0.29	0.77	-1.98	-0.35	-2.69	-0.70	0.09	0.59	0.17	0.73	-0.35	-0.07	-0.56	0.92	2.63	-0.59	-0.35	-0.67	0.43	1.56
1001	-1.06	0.14	0.72		1.15	1.01	0.47	-1.06	-1.06	1.63	0.39	-0.26	0.08	-0.53	-0.62	-0.84	-0.63	-0.57	1.11	0.47	-1.01	1.14	-0.66
2002	13.37	3.25	-0.23	3.08		-2.08	-1.34	-6.77	-3.65	-3.00	0.32	5.49	-3.42	-0.34	6.91	0.32	-5.15	-2.47	-2.90	1.67	1.59	-2.75	-1.91
2003	-2.48	-1.06	1.02	0.90	-3.08		-2.78	26.28	-4.51	-0.71	-3.33	-0.91	-6.60	-0.78	0.54	6.05	-0.56	-3.00	-2.31	0.23	0.86	-3.06	-0.70
3002	-1.34	-1.08	-0.35	-0.55	-2.34	-1.78		-3.13	-0.34	2.27	-0.77	-0.59	-0.43	1.32	-2.05	-1.06	5.93	1.29	1.87	0.33	-0.27	-0.08	3.16
4000	0.19	-2.95	-0.60	-1.06	6.84	1.26	0.05		17.14	-6.73	-3.68	3.32	-3.85	-1.96	3.97	-0.81	-7.17	-4.25	-1.28	3.05	3.64	-0.95	-4.16
2005	1.03	-1.40	-0.79	-1.23	-2.19	-8.39	-1.50	45.61		-1.85	-0.72	-3.53	-5.39	-1.50	-4.54	-1.36	-1.59	-0.59	-2.50	-1.50	-1.83	-2.40	-1.86
1003	-3.16	6.44	-0.84	-0.31	-1.53	1.06	2.40	-10.15	0.82		3.17	-0.77	-2.75	4.40	4.15	2.48	-4.89	-1.69	-1.67	1.40	-0.02	0.44	1.01
3004	-0.30	2.95	-0.34	-0.54	-0.27	-1.68	0.34	-4.99	-1.31	5.31		-1.55	-2.37	1.34	0.01	-1.03	1.99	-0.70	1.90	-0.66	-1.24	-1.05	4.18
1004	2.85	-0.55	-0.83	1.70	6.49	3.09	-1.59	-5.09	-0.16	0.91	-1.82		9.27	-0.59	-0.83	-1.51	-1.87	-1.68	-0.66	-0.59	-3.01	-2.55	-0.98
1005	5.11	1.04	-1.29	-2.02	0.45	3.18	-0.47	-5.77	-0.91	-5.34	-1.83	2.18		2.53	5.51	0.11	-6.56	-1.61	-3.12	1.53	1.34	7.04	-1.07
3006	-1.41	-0.15	0.63	-0.59	-1.47	1.00	0.29	-4.43	-0.42	2.16	-0.82	-0.68	1.43		-0.17	0.87	1.81	1.24	0.81	-0.71	-1.35	0.85	1.11
3007	-2.05	-2.28	-1.07	1.32	-0.09	4.54	-1.05	3.43	1.93	1.74	-1.35	3.17	7.63	-1.05		-2.23	0.73	-2.17	-3.42	-1.04	-2.87	-1.28	-2.55
3009	-0.07	1.33	0.45	2.14	-0.61	1.16	-1.04	-4.94	-2.08	0.32	3.80	-2.46	2.24	0.96	-1.17		1.80	-0.11	1.26	-1.04	-0.97	-1.67	0.70
1014	-3.63	-1.75	-1.23	-0.92	-5.10	-0.09	4.66	-15.78	-3.65	-6.01	1.32	-3.51	-6.42	0.66	1.91	0.32		12.52	7.10	-0.33	6.58	12.25	1.09
1017	-1.34	-1.08	1.65	-0.55	-2.34	0.22	2.32	-4.14	-0.34	-0.74	0.23	-1.59	-1.43	-0.68	-2.05	-1.06	9.93		3.87	-0.67	-0.28	0.92	-0.84
2024	-2.27	2.16	2.40	2.06	-2.97	-3.42	1.85	-3.72	1.72	-0.95	6.69	-2.70	-2.13	-1.15	-1.48	-1.81	2.49	3.79		-0.14	-1.17	-0.84	1.57
3016	0.74	-1.02	-0.33	-0.52	2.80	1.45	-0.63	5.17	-1.26	-1.63	-0.73	-0.50	3.71	-0.64	-1.93	-1.00	-1.94	-0.67	-0.06		-0.20	-0.02	-0.79
3017	-1.64	-1.14	-0.70	-1.09	-0.62	0.54	-1.33	1.86	-0.65	5.57	-1.53	-3.14	3.20	-0.33	-2.04	-0.10	2.92	-0.41	2.77	-0.33		-2.14	0.34
3025	-1.03	-1.64	0.46	-0.84	-1.55	1.27	0.98	-6.79	0.96	2.37	-1.17	-2.41	6.31	-1.03	-2.11	1.39	4.86	0.92	1.29	-1.02	0.06		-1.27
2058	-0.78	-0.44	0.53	0.26	-2.11	-2.02	0.10	0.18	2.22	-0.31	2.97	-0.12	-3.23	0.10	-2.72	2.59	1.25	0.05	0.50	-0.90	2.30	-0.44	

CHI SQUARE STATISTIC = 1455.08 WITH 483 DEGREES OF FREEDOM

Table V-5. STANDARDISED RESIDUALS

FACIES	2001	3001	5000	1001	2002	2003	3002	4000	2005	1003	3004	1004	1005	3006	3007	3009	1014	1017	2024	3016	3017	3025	2058
2001		-0.51	0.40	-0.23	1.20	-0.62	-0.03	1.04	-0.39	-0.86	-0.09	2.92	0.36	-0.30	0.03	0.03	-0.24	-0.32	-0.54	0.23	-0.09	-0.51	-0.12
3001	0.05		-0.08	0.10	0.97	1.19	-0.21	-1.73	-0.48	2.27	-0.25	-0.05	0.67	0.32	-0.23	-0.10	-0.77	-0.23	-0.39	0.06	-0.19	-0.37	0.78
5000	-0.12	0.44		-0.02	0.27	-0.46	-0.03	-0.65	-0.12	0.09	0.22	0.11	0.25	-0.03	0.04	-0.09	0.30	0.76	-0.09	-0.03	-0.12	0.18	0.47
1001	-0.22	0.10	0.25		0.37	0.33	0.18	-0.22	-0.22	0.49	0.16	-0.01	0.08	-0.08	-0.10	-0.16	-0.11	-0.09	0.35	0.18	-0.21	0.36	-0.11
2002	3.60	0.92	0.00	0.88		-0.49	-0.29	-1.73	-0.90	-0.73	0.15	1.51	-0.84	-0.03	1.89	0.15	-1.30	-0.59	-0.71	0.50	0.48	-0.67	-0.44
2003	-0.59	-0.22	0.33	0.30	-0.75		-0.67	7.01	-1.13	-0.13	-0.82	-0.18	-1.68	-0.15	0.20	1.66	-0.09	-0.73	-0.55	0.12	0.29	-0.75	-0.12
3002	-0.29	-0.22	-0.03	-0.08	-0.56	-0.41		-0.77	-0.03	0.66	-0.14	-0.09	-0.05	0.41	-0.48	-0.22	1.63	0.40	0.56	0.15	-0.01	0.04	0.90
4000	0.11	-0.72	-0.10	-0.22	1.87	0.39	0.07		4.59	-1.72	-0.91	0.94	-0.96	-0.46	1.11	-0.15	-1.83	-1.06	-0.28	0.87	1.02	-0.19	-1.04
2005	0.33	-0.31	-0.15	-0.26	-0.52	-2.15	-0.33	12.12		-0.43	-0.13	-0.87	-1.36	-0.34	-1.14	-0.30	-0.36	-0.09	-0.60	-0.33	-0.42	-0.57	-0.43
1003	-0.77	1.76	-0.16	-0.02	-0.34	0.34	0.70	-2.62	0.28		0.90	-0.14	-0.67	1.22	1.16	0.72	-1.23	-0.39	-0.38	0.43	0.06	0.18	0.33
3004	-0.02	0.84	-0.03	-0.08	-0.01	-0.38	0.15	-1.26	-0.28	1.47		-0.35	-0.56	0.42	0.06	-0.21	0.59	-0.12	0.56	-0.11	-0.27	-0.22	1.17
1004	0.81	-0.08	-0.16	0.51	1.78	0.88	-0.36	-1.29	0.02	0.30	-0.42		2.51	-0.10	-0.16	-0.34	-0.43	-0.38	-0.11	-0.09	-0.73	-0.61	-0.20
1005	1.41	0.34	-0.28	-0.47	0.18	0.90	-0.06	-1.46	-0.18	-1.35	-0.42	0.64		0.73	1.52	0.09	-1.67	-0.37	-0.76	0.47	0.41	1.92	-0.22
3006	-0.31	0.02	0.23	-0.09	-0.33	0.33	0.14	-1.11	-0.05	0.63	-0.16	-0.12	0.44		0.02	0.29	0.54	0.39	0.27	-0.13	-0.30	0.29	0.36
3007	-0.48	-0.54	-0.22	0.41	0.04	1.26	-0.22	0.97	0.57	0.52	-0.29	0.90	2.08	-0.22		-0.53	0.26	-0.51	-0.84	-0.21	-0.70	-0.28	-0.61
3009	0.04	0.41	0.18	0.63	-0.10	0.37	-0.21	-1.24	-0.49	0.15	1.07	-0.59	0.65	0.31	-0.25		0.54	0.03	0.39	-0.21	-0.20	-0.38	0.25
1014	-0.90	-0.40	-0.26	-0.18	-1.29	0.04	1.29	-4.11	-0.90	-1.53	0.41	-0.87	-1.64	0.24	0.57	0.14		3.37	1.94	-0.03	1.80	3.30	0.35
1017	-0.29	-0.23	0.50	-0.09	-0.56	0.12	0.68	-1.03	-0.03	-0.13	0.12	-0.36	-0.32	-0.12	-0.48	-0.22	2.69		1.08	-0.12	-0.01	0.30	-0.16
2024	-0.54	0.63	0.70	0.61	-0.72	-0.84	0.55	-0.92	0.52	-0.19	1.83	-0.65	-0.50	-0.24	-0.33	-0.42	0.72	1.06		0.02	-0.25	-0.16	0.48
3016	0.26	-0.21	-0.03	-0.08	0.80	0.44	-0.11	1.43	-0.27	-0.37	-0.13	-0.07	1.01	-0.11	-0.45	-0.20	-0.45	-0.12	0.05		0.01	0.06	-0.15
3017	-0.37	-0.24	-0.12	-0.23	-0.10	0.20	-0.29	0.55	-0.11	1.53	-0.34	-0.77	0.91	-0.03	-0.48	0.03	0.83	-0.05	0.79	-0.03		-0.50	0.15
3025	-0.21	-0.37	0.18	-0.16	-0.35	0.40	0.32	-1.73	0.32	0.69	-0.25	-0.58	1.73	-0.21	-0.50	0.43	1.35	0.30	0.40	-0.21	0.08		-0.28
2058	-0.14	-0.05	0.20	0.13	-0.50	-0.47	0.09	0.11	0.65	-0.02	0.85	0.03	-0.79	0.09	-0.66	0.74	0.39	0.07	0.19	-0.18	0.67	-0.05	

Table V-6. IPF PROBABILITY OF OBSERVED OR GREATER NUMBER OF TRANSITIONS OCCURRING

FACIES	2001	3001	5000	1001	2002	2003	3002	4000	2005	1003	3004	1004	1005	3006	3007	3009	1014	1017	2024	3016	3017	3025	2058
2001		-0.1095	0.1591	-0.3259	0.0437	-0.2152	-0.6059	0.1408	-0.2429	-0.0279	-0.5377	0.0000	0.3627	-0.2538	-0.6060	-0.6392	-0.3977	-0.2343	-0.0999	0.3935	-0.5253	-0.1095	-0.4949
3001	-0.6688		-0.5828	0.5713	0.0619	0.0554	-0.3554	-0.0022	-0.1250	0.0000	-0.3049	-0.5633	0.1612	0.2737	-0.3920	-0.5172	-0.0393	-0.3342	-0.1755	-0.7272	-0.4188	-0.1881	0.0384
5000	-0.4893	0.1091		-0.7464	0.3493	-0.1226	-0.6995	-0.0543	-0.4877	0.6066	0.3365	0.5743	0.3676	-0.6993	-0.7080	-0.5676	0.2957	0.0058	-0.5483	-0.6998	-0.5060	0.4384	0.0706
1001	-0.3401	0.5813	0.2453		0.2809	0.3499	0.4168	-0.4053	-0.3385	0.1557	0.4615	-0.6394	0.5822	-0.5829	-0.5125	-0.4254	-0.5076	-0.5648	0.2237	0.4164	-0.3577	0.2108	-0.5107
2002	0.0000	0.0827	-0.6530	0.0439		-0.3318	-0.3194	-0.0464	-0.0508	-0.1436	0.5031	0.0223	-0.1458	-0.5848	0.0113	0.5045	-0.0232	-0.0820	-0.0950	0.2061	0.2805	-0.1077	-0.2098
2003	-0.2374	-0.4329	0.3181	0.3749	-0.2345		-0.1067	0.0000	-0.0548	-0.4925	-0.0678	-0.4650	-0.0338	-0.4755	0.4774	0.0172	-0.5100	-0.0891	-0.2407	0.5227	0.4221	-0.1411	-0.4934
3002	-0.2558	-0.3328	-0.7007	-0.5725	-0.0889	-0.2556		-0.0952	-0.6096	0.0931	-0.4573	-0.5234	-0.5578	0.1462	-0.1211	-0.3396	0.0008	0.1597	0.1019	0.4937	-0.6340	-0.7050	0.0095
4000	0.5211	-0.1906	-0.5179	-0.4192	0.0606	0.4291	0.5535		0.0000	-0.0268	-0.0752	0.1944	-0.2072	-0.2674	0.1753	-0.4779	-0.0298	-0.0315	-0.4119	0.1257	0.1474	-0.4573	-0.0528
2005	0.3451	-0.3027	-0.4540	-0.2898	-0.2295	-0.0001	-0.2202	0.0000		-0.2534	-0.4854	-0.0268	-0.0037	-0.2199	-0.0092	-0.3123	-0.3198	-0.5275	-0.0785	-0.2206	-0.2201	-0.0869	-0.1517
1003	-0.0396	0.0011	-0.4307	-0.6223	-0.3438	0.4046	0.0764	-0.0002	0.3933		0.0368	-0.4766	-0.1641	0.0054	0.0526	0.1078	-0.0064	-0.1809	-0.2492	0.2144	-0.6431	0.4747	0.3195
3004	-0.6244	0.0203	-0.7074	-0.5810	-0.6003	-0.2725	0.4848	-0.0045	-0.2637	0.0012		-0.2048	-0.0859	0.1400	0.6003	-0.3494	0.1390	-0.4952	0.0958	-0.5156	-0.2823	-0.3427	0.0012
1004	0.0956	-0.5282	-0.4323	0.1425	0.0084	0.1755	-0.2005	-0.0685	-0.6098	0.3886	-0.1580		0.0005	-0.5254	-0.4668	-0.2810	-0.2750	-0.1822	-0.5015	-0.5267	-0.0467	-0.0747	-0.4087
1005	0.0252	0.3635	-0.2720	-0.1297	0.4866	0.2171	-0.5506	-0.0879	-0.4528	-0.0113	-0.2223	0.2276		0.1029	0.0371	0.5478	-0.0037	-0.2612	-0.0793	0.2339	0.3242	0.0022	-0.4047
3006	-0.2361	-0.6813	0.3138	-0.5540	-0.2818	0.3708	0.5140	-0.0205	-0.5817	0.1094	-0.4368	-0.4931	0.2545		-0.6301	0.3111	0.1729	0.1747	0.3360	-0.4864	-0.2527	0.3187	0.2227
3007	-0.2241	-0.1558	-0.3398	0.2364	-0.5850	0.1056	-0.3906	0.2057	0.2231	0.2736	-0.3166	0.1105	0.0065	-0.3899		-0.1632	0.4378	-0.1118	-0.0308	-0.3912	-0.0972	-0.3581	-0.0759
3009	-0.6581	0.2347	0.4232	0.0543	-0.5074	0.3669	-0.3484	-0.0332	-0.1202	0.5064	0.0068	-0.0804	0.1715	0.2809	-0.3791		0.2139	-0.6968	0.2530	-0.3489	-0.4085	-0.1823	0.3737
1014	-0.0515	-0.2720	-0.2915	-0.4267	-0.0348	-0.5628	0.0093	-0.0000	-0.0507	-0.0021	0.2806	-0.0824	-0.0081	0.4156	0.2791	0.5049		0.0000	0.0019	-0.5859	0.0049	0.0000	0.3316
1017	-0.2554	-0.3324	0.0489	-0.5721	-0.0886	0.5322	0.0297	-0.0269	-0.6091	-0.4764	0.5431	-0.1958	-0.2901	-0.5051	-0.1208	-0.3391	0.0000		0.0050	-0.5059	-0.6334	0.2955	-0.4273
2024	-0.0986	0.1119	0.0225	0.0681	-0.0860	-0.1034	0.1072	-0.1136	0.1936	-0.4298	0.0000	-0.0628	-0.2090	-0.3137	-0.3163	-0.1595	0.1372	0.0073		-0.6821	-0.3574	-0.4472	0.1708
3016	0.3599	-0.3551	-0.7155	-0.5916	0.0654	0.2796	-0.5266	0.0162	-0.2756	-0.1874	-0.4789	-0.5549	0.0241	-0.5262	-0.1371	-0.3618	-0.1346	-0.5069	-0.7132		-0.6614	-0.7287	-0.4496
3017	-0.2534	-0.3649	-0.4952	-0.3321	-0.5059	0.4741	-0.2601	0.3100	-0.5022	0.0069	-0.2130	-0.0400	0.1054	-0.6134	-0.2224	-0.6490	0.1126	-0.5863	0.0720	-0.6145		-0.1137	0.4961
3025	-0.3927	-0.1881	0.4172	-0.4287	-0.3021	0.3483	0.2732	-0.0022	0.3336	0.1218	-0.3049	-0.0843	0.0032	-0.3549	-0.1745	0.2186	0.0121	0.2956	0.2442	-0.3558	0.5812		-0.2754
2058	-0.4650	-0.5758	0.3769	0.5238	-0.1734	-0.2452	0.5960	0.5339	0.1023	-0.5925	0.0193	-0.6448	-0.0350	0.5964	-0.0603	0.0524	0.2944	0.6172	0.4445	-0.4045	0.0887	-0.5758	

NOTE: A "negative" probability represents the probability of the observed or FEWER number of transitions occurring

One can thus assign a probability to the occurrence of large residuals. The residuals are then evaluated for significant deviation from randomness using binomial probability tests of significance (Table V-6).

Markov Analysis Results

Three "preferred" vertical successions are resolved by the Markov analysis of the McMurray facies. A discrete vertical facies succession is defined by the fact that it begins with a facies to which no other facies has a preferred transition, and it ends with a facies from which there is no preferred transition.

One succession consists of a simple linear coarsening upward succession of 5 facies (Fig. V-9) beginning with intensely bioturbated, silty shale containing a moderately diverse, somewhat stressed *Cruziana* ichnofacies, with elements of a *Skolithos* ichnofacies. The succession develops vertically by becoming coarser and sandier upwards and, although the intensity of bioturbation remains relatively abundant, the ichnocoenoses slowly evolve into an assemblage dominated by the *Skolithos* ichnofacies. This succession is interpreted as constituting a low energy shoreface, but the ichnofossil signature indicates a stressed overprint which is typical of brackish conditions: high abundance, but low diversity of ichnotaxa; presence of an impoverished marine assemblage; presence of elements of both *Cruziana* and *Skolithos* ichnofacies; morphologically simple structures dominate the assemblage, indicating simple feeding strategies, and a tendency towards dwarfism is observed (Beynon *et al.*, 1988; Pemberton and Wightman, 1992; Ranger and Pemberton, 1992).

The second facies succession resolved by the Markov analysis is much more complex (Fig. V-10). The lower contact is an erosional scour surface overlain by massive, pebbly, fine to coarse grained sand, which commonly contains brecciated shale clasts. This unit begins a series of preferred transitions, almost all of which are indicative of channel filling either as active point bars or passive abandonment fills. The succession ends in facies interpreted as brackish bay and tidal flat. It is significant that the facies in the lower part of the succession are all interpreted as freshwater fluvial environments, and the absence of ichnofossils supports this conclusion. The

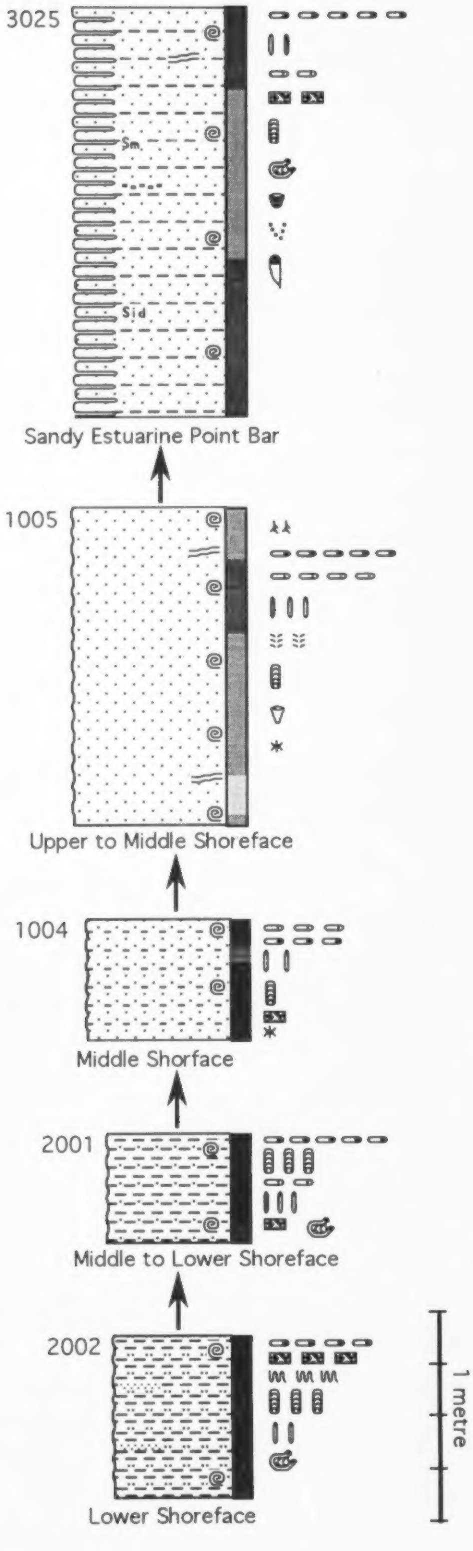
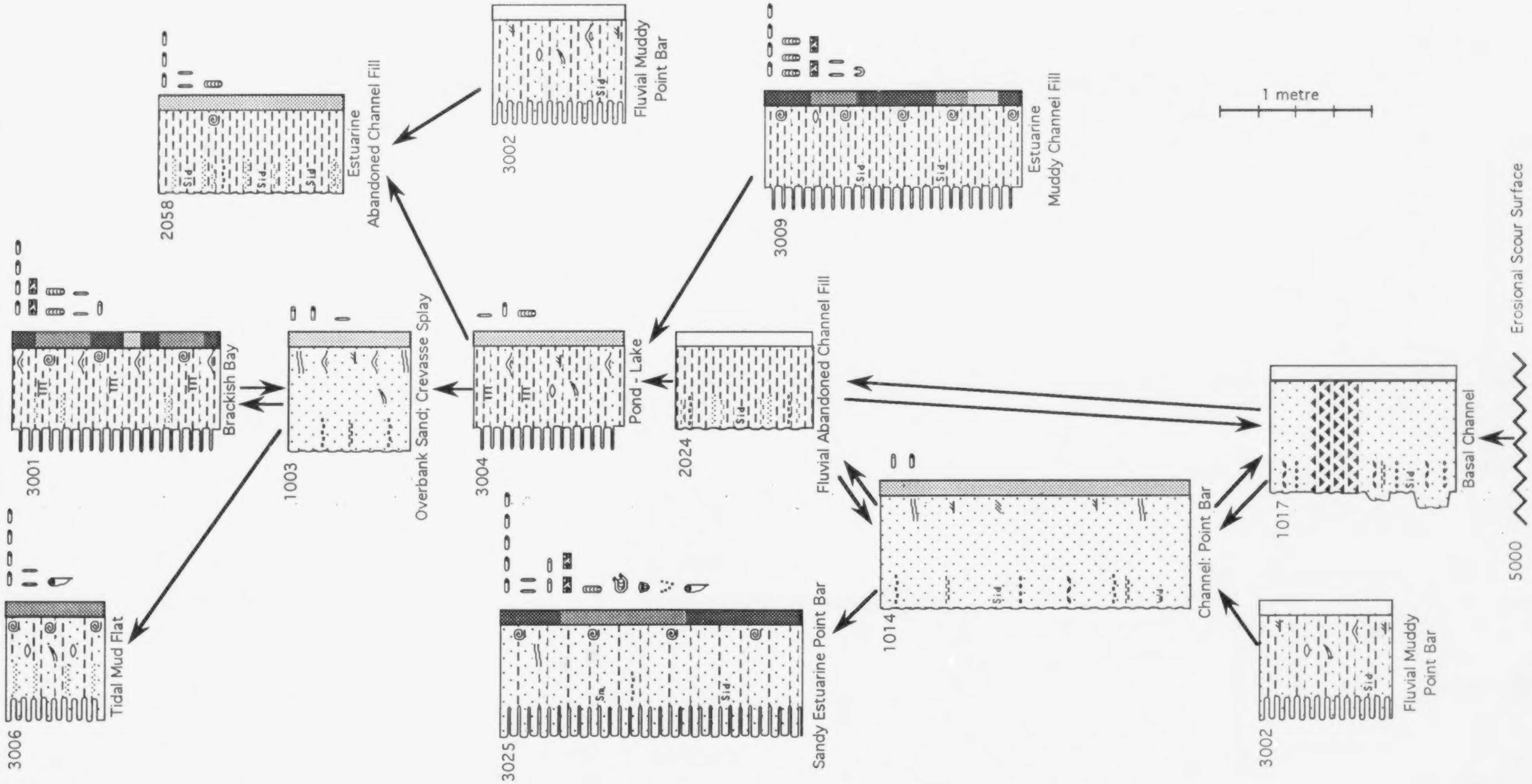

3025
Sm
Sid
Sandy Estuarine Point Bar
1005
Upper to Middle Shoreface
1004
Middle Shorface
2001
Middle to Lower Shoreface
2002
Lower Shoreface
1 metre

Figure V-9. "Preferred" succession of facies resolved from Markov analysis, and interpreted as a low energy prograding shoreface.

Figure V-10. "Preferred" succession of facies resolved from Markov analysis, and interpreted as interrelated complex channel fills. Succession is freshwater fluvial towards the base, becoming brackish estuarine towards the top.


2058
Estuarine
Abandoned Channel Fill
3002
Fluvial Muddy
Point Bar
3009
Estuarine
Muddy Channel Fill
1 metre
3001
Brackish Bay
1003
Overbank Sand; Crevasse Splay
3004
Pond - Lake
2024
Fluvial Abandoned Channel Fill
1017
Basal Channel
5000
Erosional Scour Surface
3006
Tidal Mud Flat
3025
Sandy Estuarine Point Bar
1014
Channel: Point Bar
3002
Fluvial Muddy
Point Bar
Sid

upper part of the succession has a brackish overprint, expressed mainly by the ichnofossil assemblages, as described above. The interbedded point bar deposits are interpreted as inclined heterolithic stratification characteristic of the estuarine environment (Smith, 1988; Ranger and Pemberton, 1992)

The third facies succession from the Markov analysis (Fig. V-11) is a simple system interpreted as marsh/ lagoon overlain by rooted horizons, coal swamps, rooted marsh mud and oxidised muddy paleosols.

Cross Sections From Digitised Geophysical Logs

The statistical facies analysis must be put into a regional context. This can only be done using geophysical well logs, which provide much greater coverage of the subsurface than core alone. For lithofacies detection, the gamma-ray log is the preferred tool in this study because the other tools commonly used, the SP and resistivity, are both influenced by the bitumen saturation in the sand and also by variability in formation water salinity, which can be extreme in the shallow Mannville Group. Working cross-sections were produced in both east-west (township) and north-south (range) orientations over the whole of the south Athabasca study area. The unique digital display of the gamma-ray logs as mirror images allowed rapid visual correlation of stratigraphic units with in the McMurray Formation.

The resistivity log is useful for determining the top of the Wabiskaw Member, which is a basin-wide shale with a distinct resistivity signature, and probably constitutes a condensed section. The contact between the top of the McMurray Formation and the Wabiskaw Member is not obvious on the gamma-ray logs or any other log, and this horizon had to be tied into the core observations. The contact is almost always distinctive in core, being characterised by a change in mineralogy from orthoquartzites of the McMurray Formation to glauconitic litharenite of the Wabiskaw Member. There is also a distinct change in ichnofossil assemblages from a stressed, apparently brackish assemblage in the McMurray to a robust, apparently more fully marine assemblage in the Wabiskaw Member.

The sub-Cretaceous unconformity also is rarely recognisable on the gamma-ray logs, but is distinctive on density logs.

Despite the commonly held belief that there are no regional correlatable

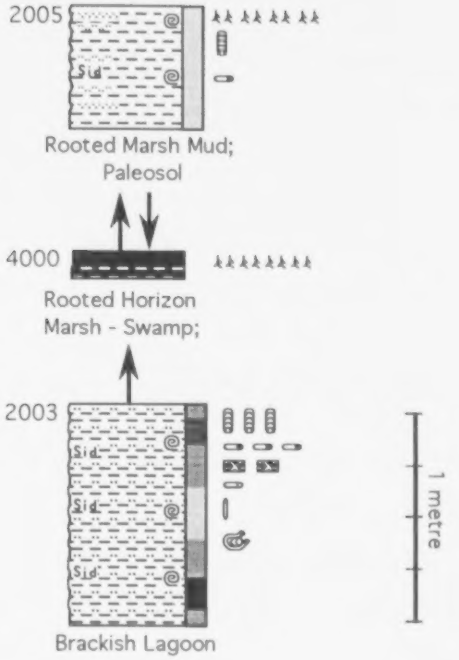

2005
Sid
Rooted Marsh Mud;
Paleosol
4000
Rooted Horizon
Marsh - Swamp;
2003
Sid
Sid
Sid
Brackish Lagoon
1 metre

Figure V-11. "Preferred" succession of facies resolved from Markov analysis, and interpreted as marsh/ lagoon overlain by rooted horizons, coal swamps, rooted marsh mud and oxidised muddy paleosols horizons in the McMurray Formation, the processed, standardised, digital log displays reveal that several regional shale units are readily discerned (Figs. V-12, V-13). Furthermore, these shales bound stratigraphic units whose log signatures are recognisable over a wide area, in both an east-west (Fig. V-12) and north-south direction (Fig. V-13). The three upper stratigraphic units are especially obvious. These are here termed the "red", "green" and "blue" intervals rather than assigning rank designation because additional study may allow further subdivision. These intervals can be correlated over much of the south Athabasca area. Both the upper "red" and the lower "blue" units have a distinct gamma ray signature indicating that they constitute, for the most part, a simple coarsening upward interval, 8 to 12 metres in thickness. The middle "green" interval has a more complex log signature than the other two, and may represent amalgamated units. The upper "red" interval, which constitutes the top of the McMurray Formation appears to have an erosional upper boundary (Fig. V-13). The distinct signatures of the three units cannot, however, be correlated through all wells without fail.

There are many areas where the the signature is anomalous, suggesting that the correlatable unit has been eroded. A map of the distribution and thickness of the "blue" interval demonstrates this (Fig. V-14). The areas in black are areas where the "blue" signature is anomalous. These anomalous signatures indicate a wide variety of fining upwards, sandy, shaly or heterogeneous fills with no discernible pattern.

Many of the wells with anomalous signatures (areas shown in black, Fig. V-14), form contiguous linear areas suggestive of channels a few kilometres wide and up to 75 kilometres long.

DISCUSSION

The results of the facies analysis and the regional gamma-ray log correlations complement each other and suggest a new, comprehensive, stratigraphic framework for the McMurray Formation. The McMurray Formation did aggrade due to Early Cretaceous sea-level rise, but the standard belief that the overall vertical record reflects a transition from fluvial through estuarine to marine is a gross over-simplification.

The McMurray Formation accumulated as a series of thin parasequences,

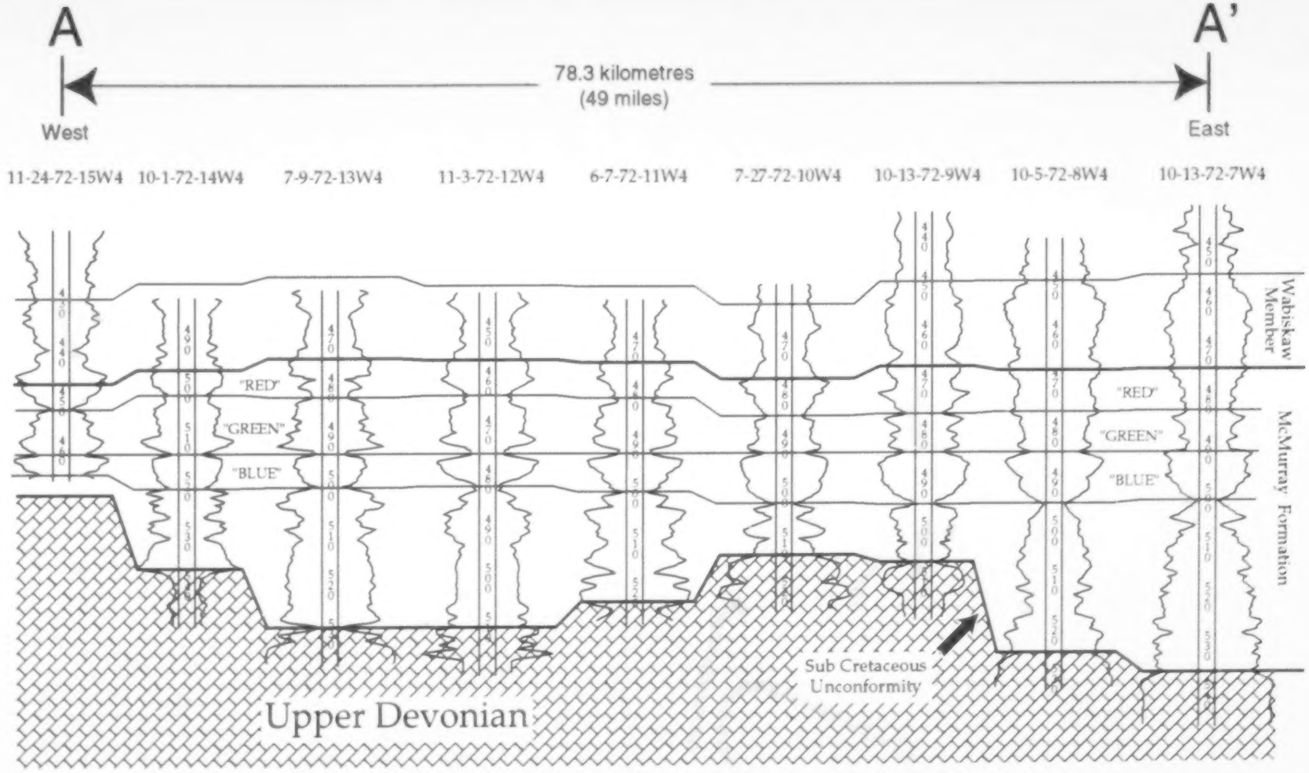

A
A'
78.3 kilometres
(49 miles)
West
East
11-24-72-15W4
10-1-72-14W4
7-9-72-13W4
11-3-72-12W4
6-7-72-11W4
7-27-72-10W4
10-13-72-9W4
10-5-72-8W4
10-13-72-7W4
Wabiskaw Member
McMurray Formation
"RED"
"GREEN"
"BLUE"
"RED"
"GREEN"
"BLUE"
Sub Cretaceous Unconformity
Upper Devonian

Figure V-12. East-west cross-section across township 72 at one well per township. This cross-section demonstrates the existence of correlateable parasequences in theMcMurray Formation. Three are shown here designated "Red", "Green" and "Blue".The datum is the top of the "Blue" parasequence, which has been mapped over the entire South Athabasca area (Figure V-14). The log curves are gamma-ray logs plotted in mirror image, which greatly facilitates the visual correlation of the shapes. For location, see A-A', figure V-14.

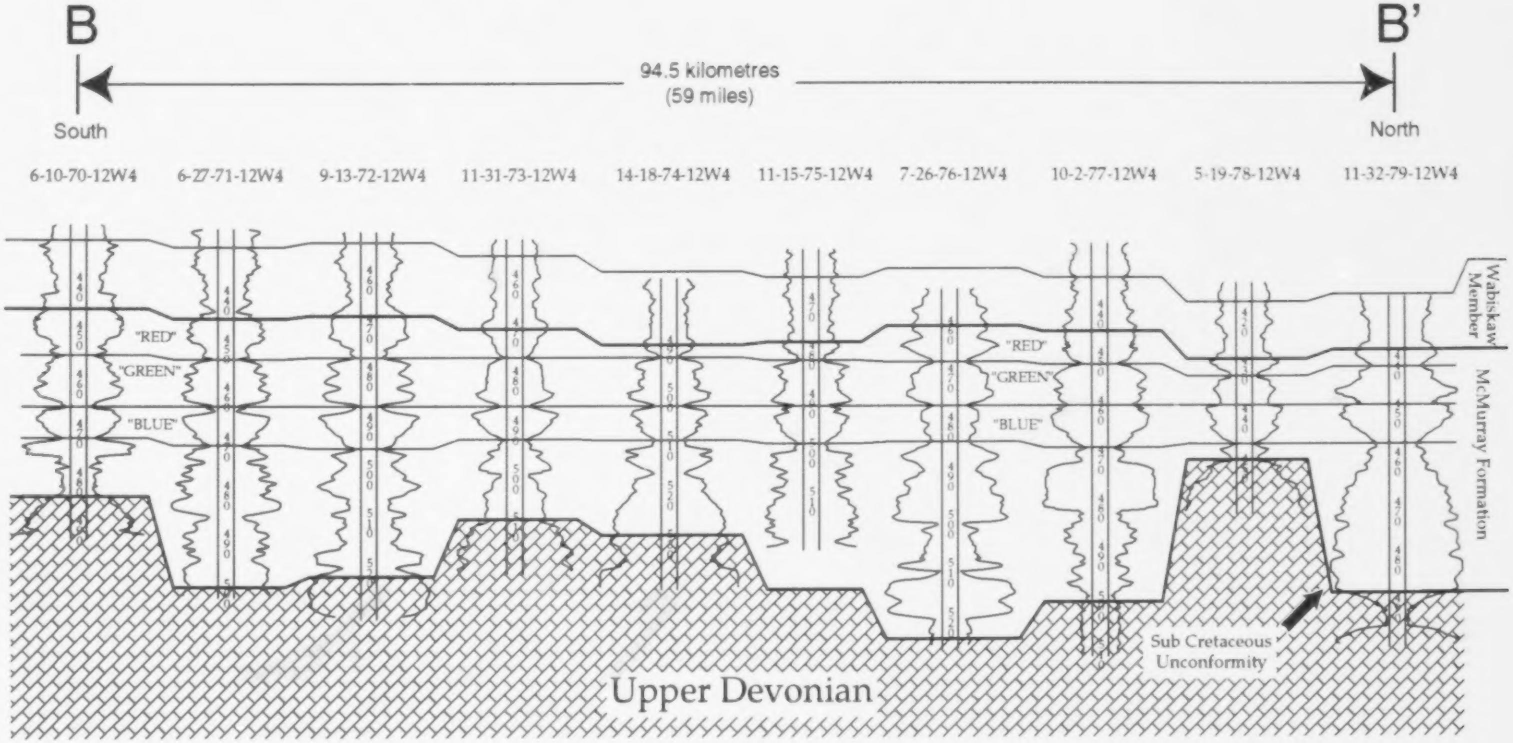
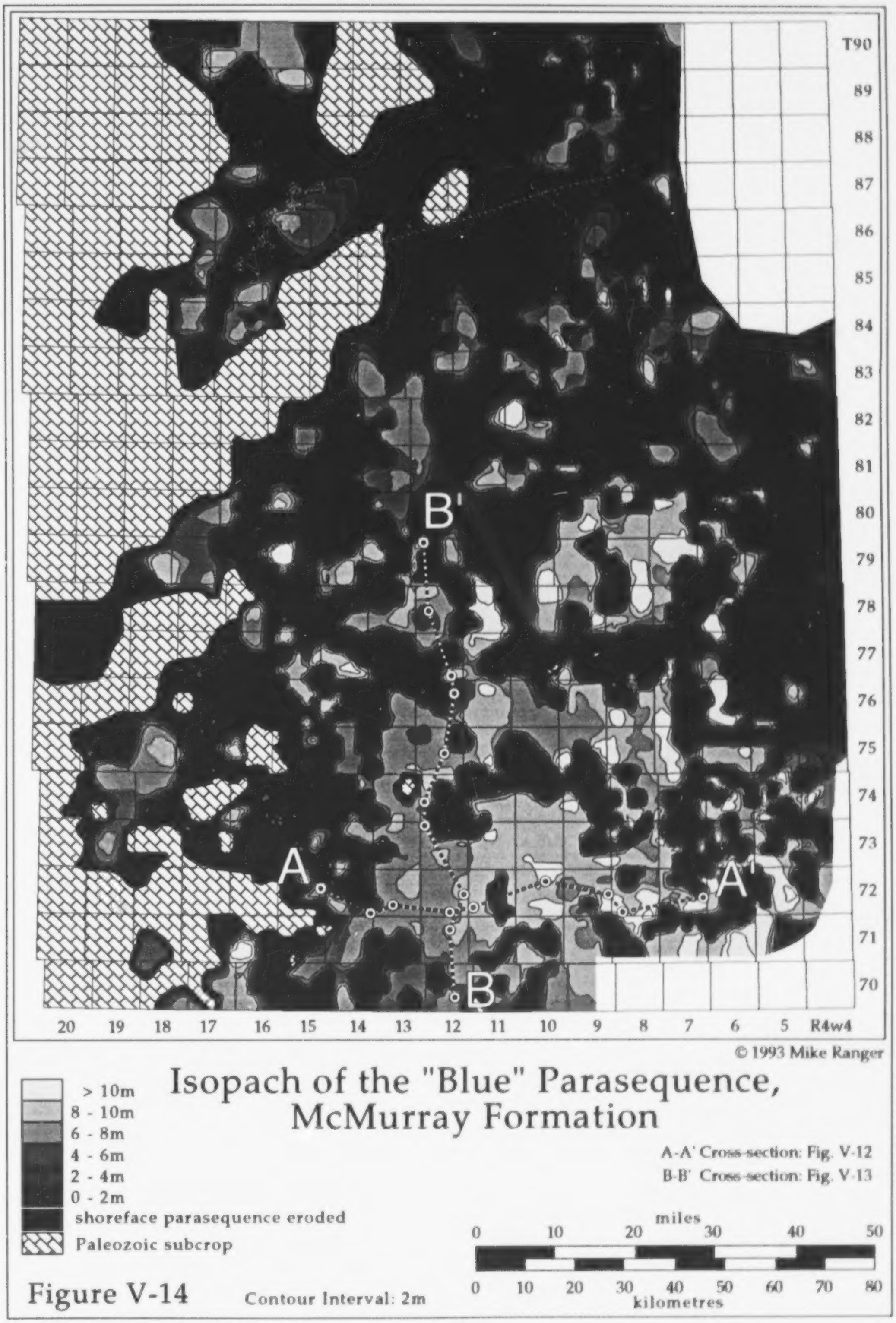

B
B'
94.5 kilometres
(59 miles)
South
North
6-10-70-12W4
6-27-71-12W4
9-13-72-12W4
11-31-73-12W4
14-18-74-12W4
11-15-75-12W4
7-26-76-12W4
10-2-77-12W4
5-19-78-12W4
11-32-79-12W4
Wabiskaw Member
McMurray Formation
"RED"
"GREEN"
"BLUE"
"RED"
"GREEN"
"BLUE"
Sub Cretaceous Unconformity
Upper Devonian

Figure V-13. North-south cross-section across range 12 at one well per township. This cross-section demonstrates the continuity to the north of the parasequences in the McMurray Formation. In fact the parasequences can be recognised and correlated over the entire study area (Figure V-14). The parasequences are designated "Red", "Green" and "Blue". The datum is the top of the "Blue" parasequence, and log curves are gamma-ray logs plotted in mirror image, to facilitate correlation. Note the existence of additional shale bounded units below the "Blue" parasequence. For location see B-B', figure V-14.


T90
89
88
87
86
85
84
83
82
81
80
79
78
77
76
75
74
73
72
71
70
B'
A
A'
B
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
R4w4
> 10m
8 - 10m
6 - 8m
4 - 6m
2 - 4m
0 - 2m
shoreface parasequence eroded
Paleozoic subcrop
miles
0
10
20
30
40
50
0
10
20
30
40
50
60
70
80
kilometres

© 1993 Mike Ranger

Isopach of the "Blue" Parasequence, McMurray Formation

A-A' Cross-section: Fig. V-12
B-B' Cross-section: Fig. V-13

Figure V-14

Contour Interval: 2m

8 to 12 metres in thickness, consisting of prograding shoreface deposits. The McMurray Subbasin developed near the craton at the eastern edge of the foreland basin, on the opposite side of the basin from the actively subsiding foreland trough, and underwent little subsidence. Given little accommodation space during each sea-level rise, shoreface deposits probably prograded rapidly and over long distances. Little is known of the rates and volumes of sediment input, but the McMurray channel system did drain a major part of west-central Canada including all of the southwestern Canadian Shield during late Aptian-early Albian time (Ranger, 1984), and one may surmise that the basin was not starved. Ichnofossil evidence indicates that the basin never reached fully marine conditions during aggradation of the McMurray Formation. This is probably due to the restricted nature of the northern part of the basin caused by the convergence of the Grosmont High in the west and the Canadian Shield in the east. The continued influx of fresh water from the McMurray valley system, even during highstand sea level, induced brackish conditions and constriction in the basin prevented rapid dispersion into the boreal sea to the north.

Additionally, because of the low rate of subsidence, even a minor sea-level drop would have wide-reaching effects, exposing large areas and causing erosion and destruction of the highstand shoreface deposits by channels cutting down to base level. Subaerial exposure would have been accompanied by the development of paleosols, and rooted horizons.

During subsequent sea-level rise the channel systems began to aggrade and fill first with fluvial sediments and then, as the channels became flooded, brackish estuaries would form. The dominant estuarine deposits appear to be sand- or mud-dominated, interbedded point bar deposits. At this point destruction of the old shoreface parasequence set would slow, and then end, as a marine flooding surface develops. The subsequent highstand sea level would then set the stage for the development of a new prograding shoreface parasequence set.

There is no evidence of a major phase of transgressive erosion at the base of any of the parasequences, not unexpected in a low energy, restricted basin. As a consequence, it is difficult to relate lowstand incision events to a particular stratigraphic horizon, or to assign the parasequences to parasequence sets, and this has not been attempted in this study.

The three uppermost parasequences in the McMurray Formation are the best preserved. In general, the older the shoreface parasequence, the more poorly preserved it is. In other words there is a bias toward the presence of lowstand channelised deposits at the expense of the shoreface deposits with depth. There is a simple explanation for this. During early McMurray time, the influence of the sub-Cretaceous unconformity was great and extensive exposed carbonate ridges separated the McMurray subbasin into long narrow valleys. Lowstand channels would have been more confined early in the depositional history of the McMurray Formation and it is likely that the channels would destroy all or most of any existing highstand shoreface by migrating from valley wall tc valley wall.

Later, as the valleys in the basin became filled and the carbonate ridges were covered, shoreface deposits would have had much wider areal development, and thus more potential for preservation from destruction. Furthermore, the channels would still have tended to avoid migrating over the old buried ridges. Due to differential compaction, these ridges would still have had a slight topographic expression, even in late McMurray time. Thus it can also be expected that the shoreface deposits exposed during lowstand sea level would be preferentially preserved over these topographic highs. This is observed in the distribution map of the "blue" parasequence (Fig. V-14), where in several areas the shoreface appears to be preferentially preserved over buried ridges on the sub-Cretaceous unconformity (see ranges 6 and 7 between townships 72 and 79).

This then can explain the standard belief that the overall vertical record of the McMurray Formation reflects a transition from fluvial through estuarine to marine. In fact there does not appear to be any fully marine environments in the McMurray Formation of south Athabasca, and the perceived lower fluvial developing to upper estuarine is simply preservational bias.

The three facies successions suggested by the Markov analysis fit the proposed depositional model. The simple shoreface succession is the preserved parasequence. It starts with a flooding surface on which is developed the lower shoreface. There is no facies that has a preferred transition to the lower shoreface, which is what is expected below a flooding surface. A flooding surface abruptly blankets all environments.

The complex channel fill succession is the expression of the lowstand erosion of the shoreface sets and subsequent filling of the channel systems. It is floored by a major erosional scour surface to which no facies has a preferential transition. Again one would expect little else but to observe any "random" facies below an erosional scour. The channel fill succession is typically fluvial at the base becoming brackish estuarine as sea level subsequently rises.

The simple paleosol/marsh succession also has no facies with a preferred transition into it. This is what one would expect because the succession is an expression of subaerial exposure, and during sea-level lowering any facies at "random" may be exposed by channelised erosion.

The paleosol/marsh succession also has no preferred transition to any specific facies. Subaerial exposure surfaces may occur in channel valleys and be covered by fluvial pointbars or a crevasse splay or estuarine deposits during sea-level rise or, in any setting, they may be abruptly covered by a flooding surface.

The top of the McMurray Formation in south Athabasca is a significant erosional unconformity surface. This is evident from the log cross-sections (Fig. V-13) where the upper "red" parasequence is commonly truncated, and its interval varies greatly in thickness compared to the older parasequences. Remnants of a parasequence younger than the upper "red" interval may even be preserved in some wells (Fig. V-12, well 10-13-72-9W4). The nature of this unconformity is revealed by the presence in some areas of deep channel deposits, constituting a single genetic unit, that carve through the McMurray Formation, erasing the entire history of the parasequence development (Ranger and Pemberton, 1992). These channels appear to be related to the unconformity surface at the top of the McMurray Formation, and may cut down right to the sub-Cretaceous unconformity surface. The unconformity at the top of the McMurray is probably the result of a major sea-level lowering. The resulting deep channels make excellent reservoirs where they are sand-filled (Ranger and Pemberton, 1992). It is significant that no paleosols, rooted horizons or other evidence of exposure have been recognised at the

McMurray-Wabiskaw contact; therefore this surface probably also corresponds to a transgressive surface of erosion, which heralded the transgression of the Clearwater sea.

Other major deep channels that cut through the McMurray Formation, up to 40 metres deep, are well known in north Athabasca in the shallow, surface mineable and outcrop areas, the best known being those cropping out at the Steepbank River (Mossop, 1980; Flach and Mossop, 1985). These well-studied examples are also interpreted to result from a major episode of sea-level lowering (Mossop, 1980). The north Athabasca deep channeling event may be older than the subsurface channels in the south however, because in the north, the channels are apparently overlain by a widespread marine unit identified as "upper" McMurray (Mossop, 1980). Therefore the northern channels may not be related to the erosion surface that characterises the top of the McMurray Formation in the south. The precise stratigraphic relationship of the McMurray Formation in north Athabasca to that in the south Athabasca study area is, as yet, unknown, because a regional stratigraphy has so far been elusive for the north Athabasca area; and this may remain so, given that the correlatable parasequence stratigraphy discovered for the southern study area may be difficult to apply farther north. It can be observed on the distribution map of the "blue" parasequence, for example, that preservation of the shoreface, the key to the stratigraphic correlations, is significantly poorer in the north than in the south.

The top of the the McMurray Formation is deeply eroded in the Primrose - Kirby area (townships 73-74, ranges 7, 8 and 9W4). Major sand-filled channels in this area constitute important bitumen reservoirs (Dekker *et al.*, 1987). These channels are younger than the McMurray Formation, apparently Wabiskaw in age, and must also represent a major sea-level lowering. As yet, it is unknown how these channels are related to regional Wabiskaw stratigraphy.

The only other comprehensive facies study of the McMurray Formation in the south Athabasca study area is that of Nelson and Glaister (1978). This is a significant study because it is a detailed facies examination and interpretation, albeit in a relatively small area of about nine townships and using information from only 28 wells. Nelson and Glaister recognised three fundamental time-stratigraphic units separated by persistent shale markers, and they were the first to recognise the thin, coarsening-upwards successions as the development of prograding shoreface complexes. They assigned these environments to deltaic development and, where channelised deposits dominated (in the northeast of their study area), they assigned these to a fluvial-dominated, nearshore, distributary system of the proximal delta. Where the ichnofossil assemblages are examined, it is evident now that there is a definite brackish overprint on the sediments in Nelson and Glaister's study area, which is indicative of estuarine, rather than deltaic conditions.

Furthermore, all of the three parasequences studied in detail in the present regional study are contained within Nelson and Glaister's "upper" unit, and their stratigraphy was much coarser than can now be discerned with modern data and methods. Their mapped distributary systems (Nelson and Glaister, 1978: Figures 12 to 15, p. 197) are thus actually amalgamated units. The interpretation of their study area based on the present study is that these systems are not dominantly deltaic in nature. The shoreface systems are remnant shoreface parasequences prograding not from the northeast, but from the south. The channelised systems are not deltaic distributaries, but are part of a northwards or north-northeastwards draining system of lowstand tributaries cutting into these exposed highstand shoreface systems tracts. The channel fills may be fluvial or estuarine depending on their stage of development.

Economic Implications

The recognition of widespread, correlatable parasequences in this study has great economic significance for the recovery of bitumen. Beyond approximately fifty metres of burial, open pit mining of bitumen is not economically feasible. Thus practically all of south Athabasca is in the area where *in situ* recovery techniques will be required. At the present time almost all of these techniques involve heating the reservoir by fire-flooding or injection of fluids from an injection well and recovery from a nearby production well. These techniques therefore require reservoir continuity between the injection and the production wells. From an engineering standpoint, this criteria is of primary importance when selecting a production site. Obviously, the preferred areas are those containing thick, sand-filled channels, although even here there may be both lateral and vertical permeability barriers (Ranger and Pemberton, 1992). Furthermore, these sites are not common and as they constitute sinuous, migrating channels, can be laterally unpredictable. On the other hand, the sandy shoreface parasequences are laterally and vertically continuous and correlatable. It is shown in this study that, knowing the detailed stratigraphy, it is possible to map the erosional channel systems that cut through the highstand shoreface sands. Avoiding the channel trends with their complex fills reduces reservoir continuity problems.

One negative aspect of targeting the shoreface parasequence sands for bitumen recovery schemes is that they are relatively thin, generally 8 to 12 metres in thickness. In addition, the shoreface sands become increasingly shaly downward, and they are therefore an increasingly poorer reservoir toward the bottom of each parasequence. It should be noted, however, that in the Wabasca area on the western edge of the Athabasca Deposit, Wabiskaw sands of a similar thickness and geometry to the McMurray shoreface parasequences (Ranger, *et al.*, 1988) have been explored and tested for many years as potential sites for commercial bitumen recovery projects. In recent years horizontal drilling has been utilised with some success in recovering low viscosity heavy oil on primary production from the Wabiskaw sands in the Wabasca area. Horizontal drilling may have potential to become a practical part of an *in situ* recovery strategy for the thin but laterally continuous shoreface reservoir sands in south Athabasca. It also cannot be ruled out that potential sites will be found in south Athabasca where bitumen viscosities are low enough to make primary recovery feasible.

CONCLUSIONS

The McMurray Formation can be stratigraphically subdivided into correlatable genetic units, 8 to 12 metres in thickness, that are persistent over wide areas, and are separated by marine flooding surfaces. These units consist of coarsening-upwards, shoreface parasequences representing highstand systems tracts, and have a distinct gamma-ray log signature. Lowstand systems tracts are also common and constitute complex fills in channels that eroded the shoreface parasequence sets.

Facies from the shoreface show a distinct brackish water overprint expressed mainly in the ichnofossil assemblages. The channel complexes are primarily filled with estuarine point bar deposits that may be shale dominant or sand dominant. However the basal fill in the deeper channels is commonly fluvial in nature. The dominantly brackish nature of the basin is probably a result of a constriction at its mouth formed by the convergence of the Grosmont High and the highlands of the Canadian Shield, which prevented dispersion of fresh water into the boreal sea.

The commonly held belief that the McMurray Formation becomes increasingly more marine upwards is probably oversimplified. There appears to be a preservational bias towards channelised systems in the lower part of the McMurray Formation, and shoreface systems towards the top.

The economic potential of south Athabasca may be enhanced by applying the new stratigraphic framework. Mappable, predictable reservoir geometry may produce new targets for *in situ* recovery schemes, even though each genetic unit is relatively thin.

Legend

Lithology

⁘	sand / sandstone
⁘	shaly sand
▤	shale / mudstone
▤	sandy shale
▩	organic shale
■	coal
▤	silty mud
⁘	silt
▧	sand with brecciated mud clasts
▤	interbedded mud > sand
▤	interbedded sand > mud

Ichnofossil Relative Abundance

⬬⬬⬬⬬⬬	Very Abundant
⬬⬬⬬⬬	Abundant
⬬⬬⬬	Common
⬬⬬	Moderate
⬬	Rare

Bioturbation Relative Intensity

■	Abundant
▩	Common
▦	Moderate
░	Rare
□	Nil

Physical Structures

⌒	current ripples
︿	symmetrical ripples
///	high angle planar lmaination
≈	low angle planar lamination
~	flaser bedding
⬭	lenticular
@	churned or chaotic bedding
╥╥	syneresis cracks
......	sand lamina
----	shale lamina
••••	pebble - granule horizon
Sid	sideritic
~~	rip-up clasts
-•-•-	coal - organic fragments

Ichnofossils

⅄⅄	rootlets
⬬	*Planolites*
⬭	*Palaeophycus*
∴	*Gyrolithes*
U	*Arenicolites*
≋	Escape Trace
@	*Rhizocorallium*
∪	*Cylindrichnus*
∇	*Bergaueria*
∇	*Conichnus*
✱	*Asterosoma*
▪	*Chondrites*
▯	*Teichichnus*
ᴍ	*Helminthoida*
ǀ	*Skolithos*

Figure V-15

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CHAPTER VI

LOWER CRETACEOUS EXAMPLE OF A SHOREFACE-ATTACHED MARINE BAR COMPLEX: THE WABISKAW "C" SAND OF NORTHEASTERN ALBERTA[1]

INTRODUCTION

The Lower Cretaceous Wabiskaw Member of the Clearwater Formation (Fig. VI-1) in northeastern Alberta is the lithostratigraphic equivalent of the Glauconitic Member of southern Alberta, the Cummings of eastern Alberta and the Bluesky Formation of the Peace River area. All four are important reservoir rocks for conventional oil and gas, heavy oil and bitumen. The Wabiskaw Member in the Wabasca area has been interpreted as an offshore bar (Bayliss and Levinson, 1976), a transgressive sand (Outrim and Evans, 1977), or a barrier bar (Jackson, 1984). In this study, core examination indicates that the sands developed in an offshore shallow marine environment.

In the Wabasca area three, discrete, overlapping sand bodies have been recognised within the Wabiskaw Member (ERCB, 1976; Ranger, 1982) These have been informally termed, from the top down, the Wabiskaw "A", "B" and "C" sands (ERCB, 1976). These sand bodies are reservoirs of the Athabasca Oil Sand Deposit and contain approximately 25 X 10^9 bbls of bitumen, most of which is contained in the uppermost Wabiskaw "A" sand. This study focuses on the sedimentology, geometry and ichnology of the lowermost sand body, the Wabiskaw "C" sand, which appears to have been a shallow shoreface in the south, but a deeper, offshore deposit toward the north.

SAND BODY GEOMETRY AND BASIN SETTING

Correlation of the Wabiskaw "C" sand body from well logs is

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[1] A version of this chapter has been published. Ranger, M.J., Pemberton, S.G. and Sharpe, R.J. 1988. Lower Cretaceous example of a shoreface-attached marine bar complex: the Wabiskaw "C" sand of northeastern Alberta. *In:* James, D.P. and Leckie, D.A. (eds), Sequences, stratigraphy, sedimentology: surface and subsurface. Canadian Society of Petroleum Geologists, Memoir 15, pp. 451-462.

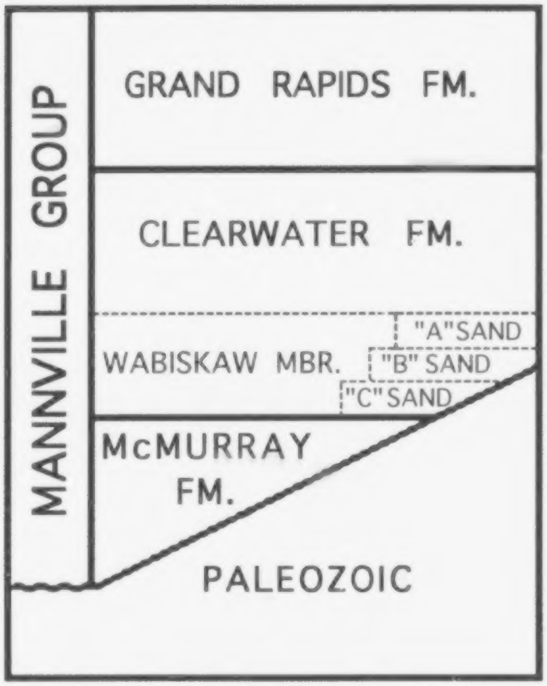

MANNVILLE GROUP
GRAND RAPIDS FM.
CLEARWATER FM.
"A"SAND
WABISKAW MBR.
"B" SAND
"C"SAND
McMURRAY FM.
PALEOZOIC

Figure VI-1. Stratigraphy of the Wabiskaw Member, Clearwater Formation.

straightforward except where it is directly overlain by the Wabiskaw "B" sand body producing an amalgamated sand (Fig. VI-2). The relatively simple three dimensional geometry, interpolated from the geophysical logs, strongly suggests that the sand is a continuous body. Its shape is elongate, striking northeastward in the south and curving northward (Fig. VI-3). The sand body is approximately 120 km long and 25 km wide and is thickest in the south, where it attains a thickness of 20 m. To the north, the sand body thins and gradually becomes an apron of very fine-grained sand and silt merging imperceptibly with the enclosing shale so that a discrete boundary is not mappable. Throughout the sand body, gamma-ray and S.P. log signatures indicate a coarsening-upward morphology (Fig. VI-2), which is substantiated by grain size analyses.

Locally, the Wabiskaw Member lies directly on paleotopographic highs of the sub-Cretaceous unconformity (e.g. townships 75 and 76, range 26W4). Over paleotopographic lows it is separated from the unconformity by valley fill deposits of the McMurray Formation. Well lithified carbonates of the Upper Devonian Woodbend and Winterburn Groups subcrop at the sub-Cretaceous unconformity, forming a relatively rigid basement for deposition of overlying Lower Cretaceous sediments. It has been observed that isopach maps of lithostratigraphic units lying directly on the unconformity can be interpreted as if they were a mould of the erosional paleotopography on the unconformity (Williams, 1963; Ranger, 1984). In this study, an isopach map of the Mannville Group (Fig. VI-3) provides just such an interpretation. The net sand isolith contours of the Wabiskaw "C" sand are shown on this map, providing evidence of the basinal setting of the Wabiskaw "C" sand. It is clear that the geographic position of the sand has been influenced by the position of a prominent, narrow valley on the unconformity surface, and it appears evident that the Wabiskaw "C" sand is, for the most part, confined to what must have been a topographic depression on the basin floor.

ICHNOLOGY

The Wabiskaw "C" sand contains an abundant and well preserved ichnofossil assemblage; representatives of 17 ichnogenera were identified, including: *Asterosoma, Chondrites, Conichnus, Cylindrichnus,*

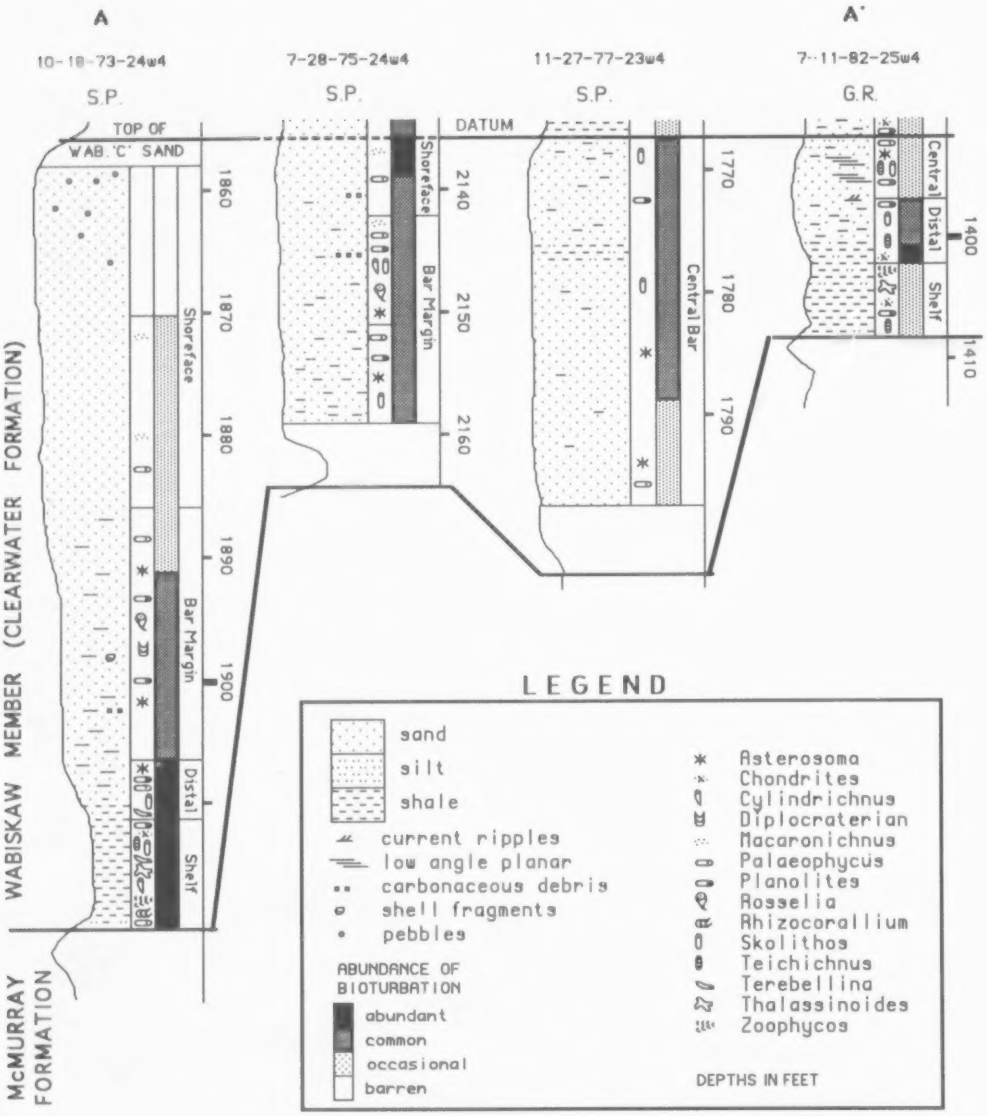

A
A'
10-18-73-24w4
7-28-75-24w4
11-27-77-23w4
7-11-82-25w4
S.P.
S.P.
S.P.
G.R.
TOP OF WAB.'C' SAND
DATUM
1860
1870
1880
1890
1900
2140
2150
2160
1770
1780
1790
1400
1410
Shoreface
Bar Margin
Distal
Shelf
Shoreface
Bar Margin
Central Bar
Central
Distal
Shelf
WABISKAW MEMBER (CLEARWATER FORMATION)
McMURRAY FORMATION
LEGEND
sand
silt
shale
current ripples
low angle planar
carbonaceous debris
shell fragments
pebbles
ABUNDANCE OF BIOTURBATION
abundant
common
occasional
barren
Asterosoma
Chondrites
Cylindrichnus
Diplocraterian
Macaronichnus
Palaeophycus
Planolites
Rosselia
Rhizocorallium
Skolithos
Teichichnus
Terebellina
Thalassinoides
Zoophycos
DEPTHS IN FEET

Figure VI-2. Descriptive north-south core cross-section through Wabiskaw "C" sand. See figure VI-3 for location A-A'.

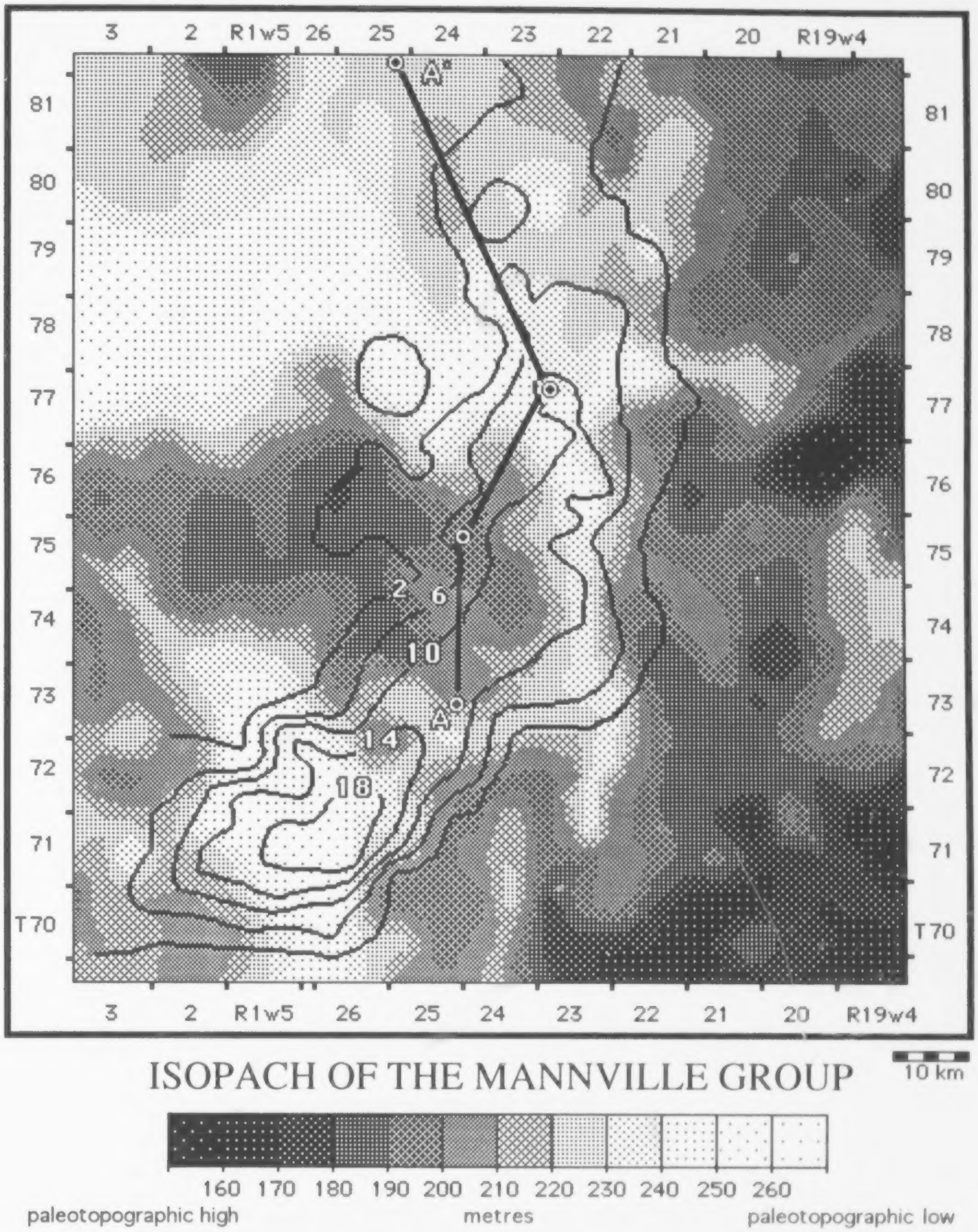

3
2
R1w5
26
25
24
23
22
21
20
R19w4
81
80
79
78
77
76
75
74
73
72
71
T70
A'
A
2
6
10
14
18
ISOPACH OF THE MANNVILLE GROUP
10 km
160
170
180
190
200
210
220
230
240
250
260
paleotopographic high
metres
paleotopographic low

Figure VI-3. Basinal setting of the Wabiskaw "C" sand. Gray shading is an isopach map of the Mannville Group. This produces a "mould" of the underlying erosional sub-Cretaceous unconformity, which is used to infer the basinal paleotopography. Black contour lines of the Wabiskaw "C" net sand (metres) show the position of the sand body relative to buried paleotopography. The sand body clearly was affected by the paleotopography and apparently lies in a depression on the basin floor. Cross-section A-A' refers to figure VI-2.

Diplocraterion, Helminthopsis, Macaronichnus, Ophiomorpha, Palaeophycus, Planolites, Rhizocorallium, Rosselia, Skolithos, Subphyllochorda, Teichichnus, Thalassinoides and *Zoophycos*. In addition, there are numerous fine-grained beds, characterised by a bioturbate texture in which individual burrow forms are difficult to discern. Likewise, numerous escape structures were noted, associated with fine-grained, parallel to subparallel laminated sandstones.

Although somewhat problematic, each ichnogenus can be attributed to 1) a particular group or groups of organisms, 2) an ethological (or behavioural) category, and 3) a general trophic group. In this way the original biotic component of the unit can be reconstructed. The Wabiskaw "C" sand, therefore, contains dwelling, feeding, locomotion and grazing structures produced by polychaetes (or other worm-like organisms), sipunculids, anemones, heart urchins, and decapod crustaceans (Table VI-1).

FACIES SUCCESSION

Four intergradational facies are recognised in the northern part of the Wabiskaw "C" sand (the facies descriptions also apply to the overlying Wabiskaw "B" and Wabiskaw "A" sands). With few exceptions, all the facies contacts tend to be both laterally and vertically gradational.

Facies 1

Facies 1 consists predominantly of fine-grained sand, commonly coarsening upwards slightly from the base. Bedding and other physical structures are difficult to see, because of bitumen saturation, or bioturbation. Consequently the sand usually appears homogeneous and massive.

In some cores, low-angle planar crossbedding is present (Fig. VI-4a). The beds have erosional lower bounding surfaces, slope at angles less than 10 degrees (but may slope up to 15 degrees), and have random dip directions. These are all characteristics of hummocky cross-stratification (Harms *et al.*, 1982). However, a key diagnostic characteristic, the systematic lateral thickening of laminae, can rarely be recognised in the relatively small width of a core.

The ichnofossil suite visible in this facies (Table VI-2) consists of a low

ICHNOGENUS	ETHOLOGICAL CLASSIFICATION	TROPHIC GROUP	PROBABLE PRODUCER
Asterosoma	fodinichnia	deposit feeder	annelid
Chondrites	fodinichnia	deposit feeder	sipunculid/annelid
Conichnus	domichnia	carnivore	anemone
Cylindrichnus	fodinichnia/domichnia	deposit feeder	annelid
Diplocraterion	domichnia	suspension feeder	crustacean
Helminthopsis	paschichnia	deposit feeder	annelid
Macaronicnus	fodinichnia	deposit feeder	annelid
Ophiomorpha	domichnia	suspension feeder	crustacean
Palaeophycus	domichnia	carnivore	annelid
Planolites	fodinichnia	deposit feeder	annelid
Rhizocorallium	fodinichnia	deposit feeder	crustacean
Rosselia	fodinichnia	deposit feeder	annelid
Skolithos	domichnia	suspension feeder	annelid
Subphyllochorda	repichnia/fodinichnia	deposit feeder	heart urchin
Teichichnus	fodinichnia	deposit feeder	annelid
Thalassinoides	domichnia	deposit feeder	crustacean
Zoophycos	paschichnia	deposit feeder	sipunculid/annelid

Table VI-1. Classification of ichnogenera recorded in the Wabiskaw "C" sand.

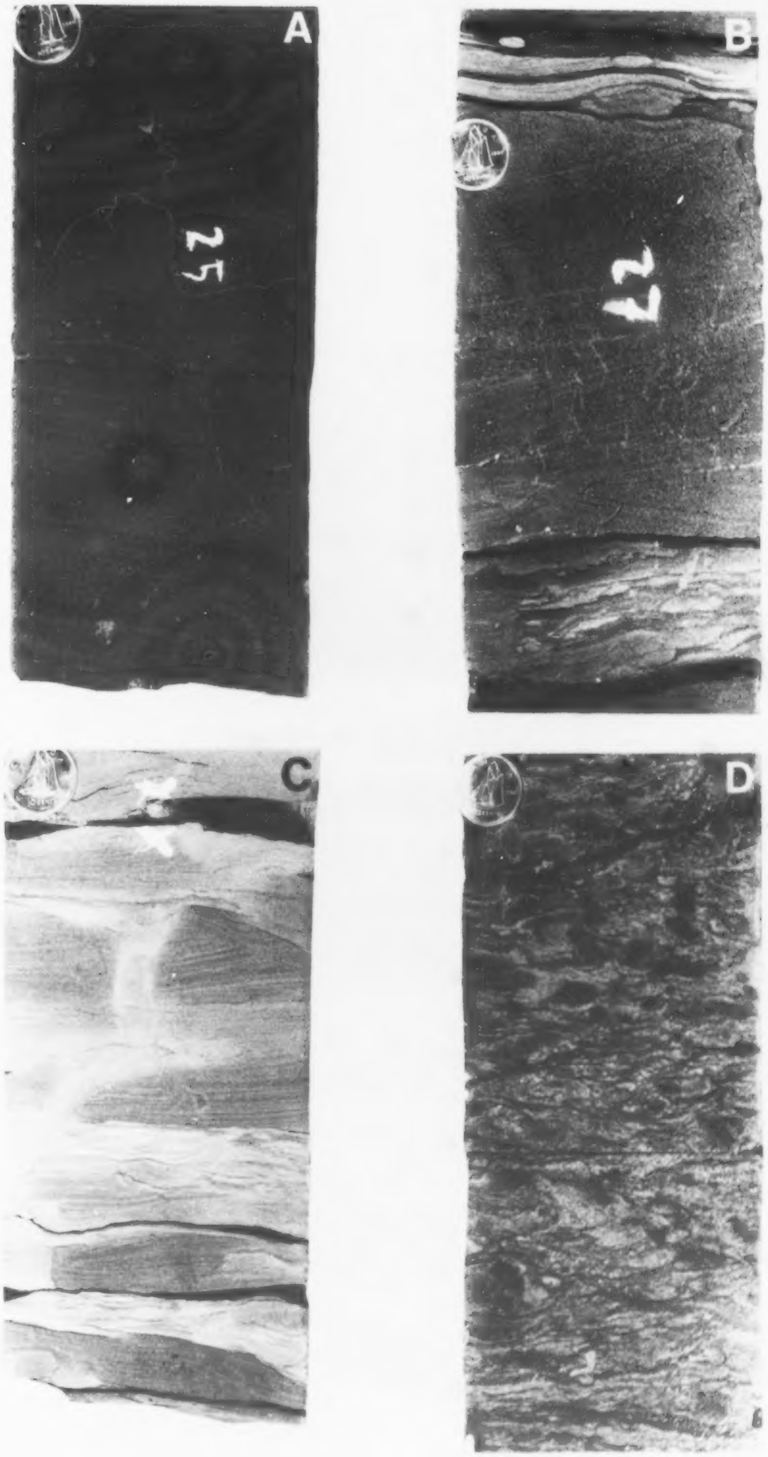
Figure VI-4. Examples of facies in core (7-11-82-25W4).

A. Probable hummocky cross-stratification from the central bar environment (1388 ft/423 m).

B. Interbedded, cross-stratified sand and laminated-burrowed silt and shale from the bar margin environment (1389.5 ft/423.5 m).

C. Large *Diplocraterion* burrow in interbedded sand and shale of bar margin environment (1395 ft/425.2 m).

D. Abundant, diverse ichnofossil assemblage of the interbar shelf (1400 ft/426.7 m).


A
25
B
27
C
D

ICHNOGENUS	FACIES / INTERPRETATION				
	1 CENTRAL BAR	2 BAR MARGIN	3 DISTAL BAR MARGIN	4 INTERBAR SHELF	5 SHALLOW SHOREFACE
SKOLITHOS	C	C	O	O	
PALAEOPHYCUS	C	C		O	
DIPLOCRATERION	R				
ASTEROSOMA	**R**	**C**	**O**	**O**	
TEICHICHNUS		**O**	**C**	**C**	**O**
CONICHNUS		O	R	R	
CYLINDRICHNUS		**R**			
OPHIOMORPHA		R			
ROSSELIA		**R**			
PLANOLITES			**A**	**C**	
CHONDRITES			**A**	**C**	
HELMINTHOPSIS				**C**	
THALASSINOIDES				**O**	
ZOOPHYCOS				**O**	
RHIZOCORALLIUM				**R**	
SUBPHYLLOCHORDA				**R**	
MACARONICHNUS					**A**

Relative Abundance :
A = Abundant
C = Common
O = Occasional
R = Rare

Outlined Letters: Feeding Structures
Normal Letters: Dwelling Structures

Table VI-2. Distribution and relative abundance of ichnogenera in the Wabiskaw "C" sand.

density assemblage of dwelling structures, mainly *Palaeophycus* and *Skolithos*, with rare *Diplocraterion* and escape structures, reflecting a mainly suspension-feeding community of infaunal organisms. Deposit feeding structures are uncommon, although some *Asterosoma* burrows are evident. Such an assemblage reflects relatively high energy levels.

Facies 2

Facies 2 is lithologically similar to facies 1, but the grain size is somewhat finer, becoming very fine grained toward the base, where discrete shale beds are more common. Bedding is not always evident, but appears to be low angle planar or cross-stratified (Figs. 4b, 4c).

The major distinguishing feature of this facies is the ichnofossil suite, which displays an overall increase in both density and diversity (Table VI-2). The suite is again dominated by dwelling burrows, commonly *Skolithos* and *Palaeophycus*, with some *Cylindrichnus*, *Conichnus* and *Ophiomorpha*. However, feeding structures such as *Asterosoma*, *Teichichnus*, and rarely *Rosselia* are also present. The dominance of dwelling structures is again consistent with high energy levels, although less so than in facies 1.

Facies 3

Lithologically, facies 3 is very fine-grained silty sand with a considerable clay content and may contain shell fragments. Sorting is poor and the lower contact is gradational into the silty clay of facies 4. Facies 3 is always highly bioturbated, and physical structures are totally obliterated (Figs. 5a, 5b). As in facies 2, the ichnofossil suite (Table VI-2) contains a mixture of dwelling (*Conichnus* and *Skolithos*) and feeding (*Asterosoma, Planolites, Chondrites* and *Teichichnus*) structures. However, dwelling burrows and feeding structures are found in approximately even numbers.

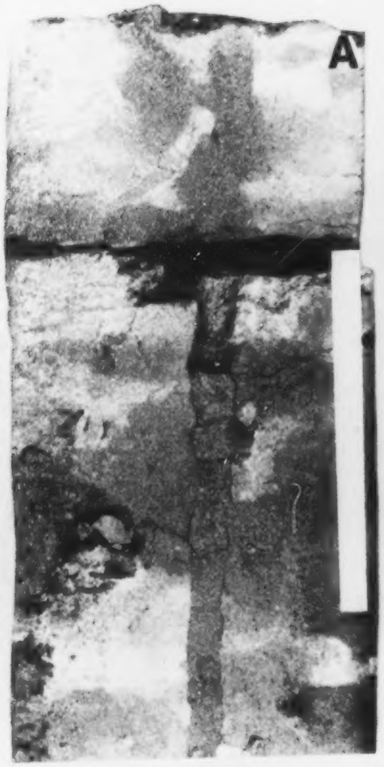
Facies 4

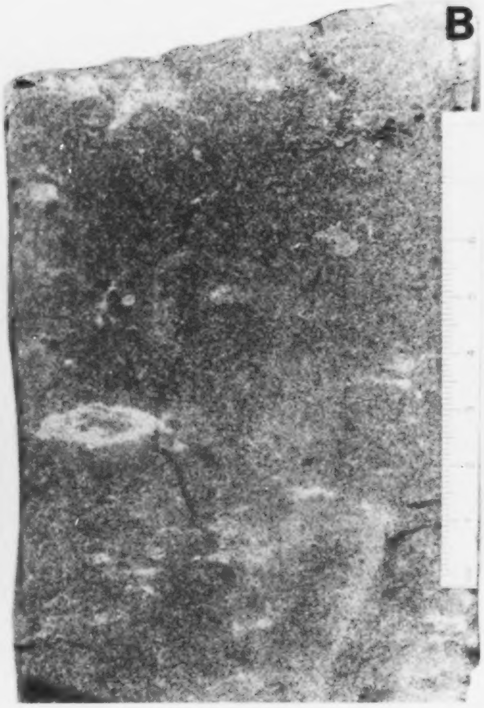
This facies constitutes the fine-grained beds in the Wabiskaw cores. The lithology is typically an intensely bioturbated silty clay lacking physical structures (Fig. VI-4d), although shale laminae may rarely be visible. The ichnofossil suite (Table VI-2) is a distinctive assemblage dominated by

Figure VI-5. Examples of facies in core (11-27-77-23W4).

A. Large *Skolithos* burrow in a bioturbate-textured, interbedded sand and shale of the distal bar margin.

B. *Palaeophycus* burrows from the bar margin (1784 ft/543.8 m).


A


B

feeding (*Asterosoma, Teichichnus, Planolites, Chondrites, Thalassinoides,* and, more rarely, *Rhizocorallium* and *Subphyllochorda*), and grazing (*Helminthopsis* and *Zoophycos*) structures. Dwelling structures such as *Skolithos, Conichnus* and *Palaeophycus* are rare. This suite records a fundamental shift in behaviour from predominantly suspension-feeding to deposit-feeding consistent with the fine-grained substrate of a low energy environment.

A distinctive and significant set of features is occasionally observed in this facies, consisting of sharp-based, apparently erosional, very fine-grained, fining upward sand beds, a few centimetres thick, which display low-angle planar laminae. They commonly contain escape structures and, more rarely, dwelling burrows (*Skolithos* and *Palaeophycus*). These features have been interpreted in outcrop as indicating episodic storm-emplaced beds (Pemberton and Frey, 1984).

Facies 5

In the southern part of the Wabiskaw "C" sand, a distinctly different facies, facies 5, appears at the top of the sand body. Its lower contact is gradational into facies 2.

Facies 5 contains little evidence of bedding due to disruption by bioturbation. The sediment is a poorly sorted, shaly sand with some discrete shale laminae or bioturbated shale pods. The sand is somewhat coarser than in other facies, becoming medium to fine grained. Granules and pebbles become a minor component towards the top. The most distinctive characteristic of the facies is the appearance of the ichnofossil *Macaronichnus segregatis* (Figs. 6a, 6b). The infill of these burrows consists solely of quartz grains, which contrasts with the predominantly lithic, glauconitic mineralogy of the burrow wall and the ambient sediment (Fig. VI-6d). Towards the base of the facies, as it gradually becomes more argillaceous, a deposit-feeder structure, *Teichichnus*, (Fig. VI-6c) is associated with *Macaronichnus*, suggesting elements of a *Cruziana* ichnofacies and probably reflecting moderate energy levels (Table VI-2).

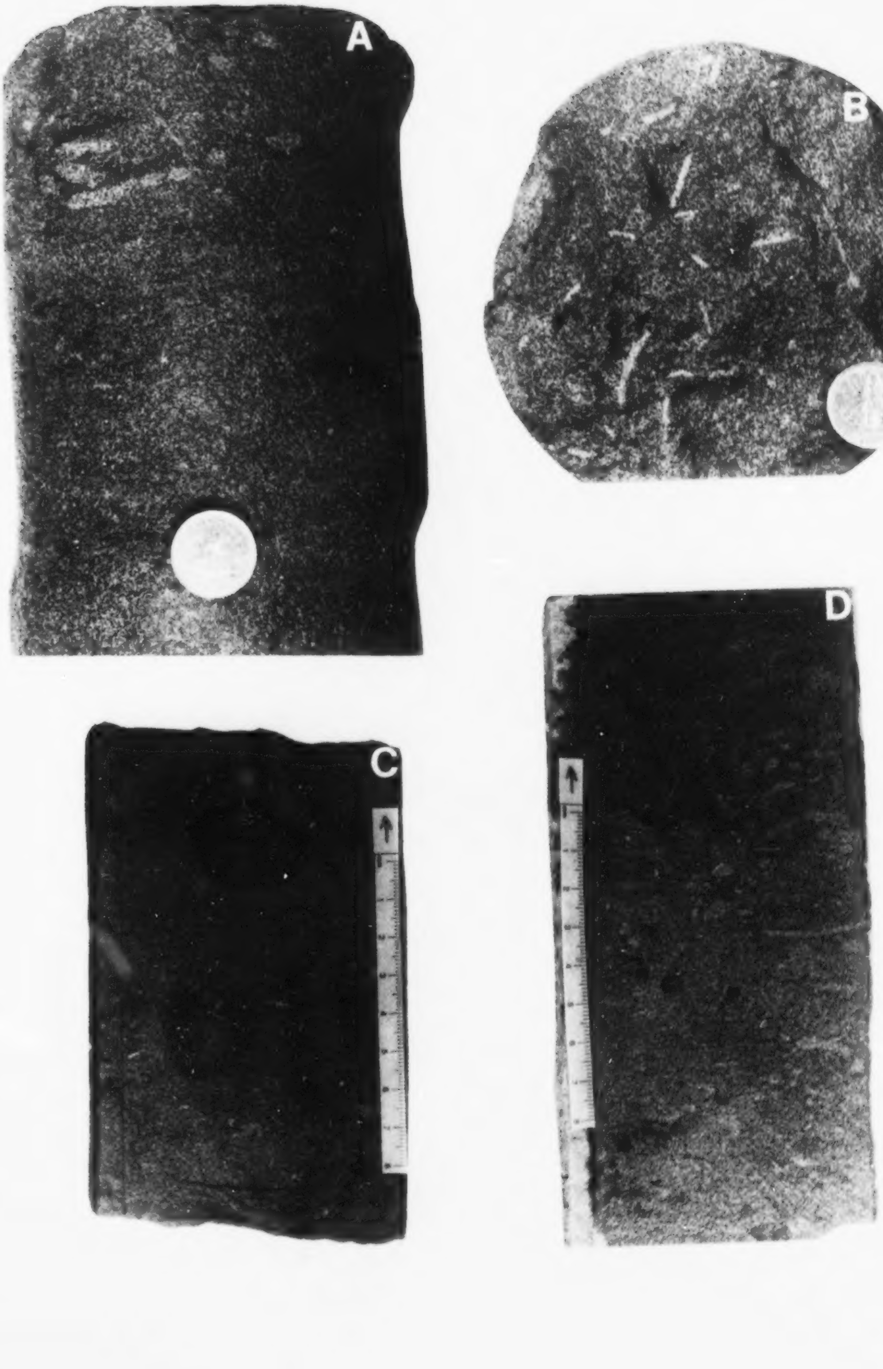
Figure VI-6. *Macaronichnus segregatis* (Facies 5), the burrow of a deposit-feeder indicative of shoreface environment:

A. Sectional view (10-18-73-24W4 1884 ft/574.2 m).

B. Bedding plane view (10-18-73-24W4 1886 ft/574.8 m).

C. In association with *Teichichnus* (facies 5: 7-28-75-24W4).

D. Abundant *Macaronichnus* on slabbed core surface illustrates feeding behaviour that selectively removes non-quartz grains. These excluded grains, the mafic, lithic, and glauconitic components, mantle the wall of the burrow (7-28-75-24W4).


A
B
C
D

DISCUSSION

Environmental Interpretation

A north-south cross-section through the Wabiskaw "C" sand (Fig. VI-2) demonstrates the facies relationships. Several lines of evidence point to the overall normal marine conditions interpreted for the Wabiskaw "C" sand. Glauconite is believed to form authigenically on the sea floor or shallow subsurface under marine conditions (Odin and Matter, 1981). The ichnofossil suites are generally diverse and abundant, and many forms are characteristic of fully marine conditions i.e. *Rhizocorallium, Zoophycos, Subphyllochorda.* Throughout the facies succession, large forms are particularly apparent, suggesting a population containing an abundance of fully mature individuals existing in non-stressful conditions. The trace makers evidently occupied niches characterised by optimal ecological conditions in a normal marine environment.

Facies Interpretation - Northern part of deposit

The facies sequence in the northern part of the Wabiskaw "C" sand suggest that it was deposited offshore as a shallow shelf bar complex with energy levels increasing from bottom to top. This is suggested simply by the coarsening upwards nature of the sediment, but more powerful evidence is provided by the distribution of the ichnofossil suites. In the lower part of the facies sequence the ichnofauna is diverse and abundant, and dominated by forms that reflect deposit-feeding behaviour (i.e., the *Cruziana* ichnofacies). The rarity of suspension-feeding structures suggests relatively low-energy levels, making suspension feeding inefficient. Upward in the succession, abundant dwelling structures dominate (i.e. the *Skolithos* ichnofacies) indicating that suspension feeding must have been a reliable feeding strategy, presumably because higher-energy conditions induced the sea water circulation required to provide a reliable influx of food. In the uppermost portion of the facies succession, the ichnofauna is less abundant and diverse, and is restricted to forms such as *Skolithos* and *Palaeophycus* created by organisms that were able to inhabit a higher energy, sandy substrate for dwelling and suspension-feeding. However the presence of some deposit-feeding structures such as *Asterosoma*, even in the higher energy, clean sands, is suggestive of an offshore origin.

The nature of the upper contact of the facies succession, where it is overlain by shale of the Wabiskaw "B", is of considerable importance. It is invariably gradational and bioturbated, and shows no evidence of transgressive erosion.

The facies succession in the northern part of the Wabiskaw "C" is therefore interpreted to be that of an offshore, marine bar. The vertical succession reflects increasing energy levels and presumably upward shallowing. Porter (1976) has provided a commonly used terminology for the components of an offshore bar, which can be applied here with little modification and which has been used by many others with minor variations to describe offshore bars and shelf ridges (e.g. Tillman and Martinsen, 1984).

Facies 1 is the central bar complex that constitutes the axis of the sand body, the highest energy zone of the bar. The probable occurrence of hummocky cross-stratification indicates an environment above storm wave base and suggests emplacement, or at least reworking of the sands by oscillatory storm processes. The central bar complex has aggraded or, more likely, prograded over a bar margin complex.

Facies 2 and 3 are interpreted as representing proximal and distal bar margin environments respectively, the distal bar margin being more argillaceous and supporting a more diverse and abundant infauna.

Facies 4 is considered to represent the interbar/shelf environment. Maximum water depths, based on the indigenous suite of ichnofossils (especially *Zoophycos* and *Helminthopsis*), can be estimated not to have exceeded 30m. This represents the approximate lower limit of the *Cruziana* ichnofacies situated at storm wave base.

To varying degrees all of these facies contain elements of both the *Cruziana* (low energy) and *Skolithos* (high energy) ichnofacies. This combination has been attributed to episodic storm events (Pemberton and Frey, 1984), wherein the resident *Cruziana* ichnofacies is disrupted by the influx of storm-generated silt and fine sand. These sediments are soon colonised by a few opportunistic species (elements of the *Skolithos* ichnofacies), which quickly attain high densities. When normal sedimentological conditions are stabilised once more, the resident fauna slowly reestablishes itself, selectively displacing the opportunistic species.

Facies Interpretation - Southern part of deposit

Facies 5, which occurs only towards the south and at the top of the Wabiskaw "C" sand body, is recognised by its distinct low-diversity trace fossil suite, dominated by *Macaronichnus*, which appears to be the burrow of a highly mobile deposit feeder (Clifton and Thompson, 1978). The organism is adapted to grazing on a granular substrate, apparently feeding on micro-organisms that colonise the surfaces of sand grains (Saunders and Pemberton, 1986). *Macaronichnus* has commonly been recognised as an infaunal burrow from a relatively high energy, foreshore to upper shoreface environment (Clifton and Thompson, 1978; Leckie, 1983; Saunders and Pemberton, 1986). The physical requirements needed to support the colonisation of this environment appears to be the maintenance of a well-oxygenated substrate with sufficient dissolved nutrients to allow the growth of the microbial (probably bacterial) food supply. Although the sediment/water interface may be exposed to high-energy physical forces, the substrate below the physical disturbance can support bacterial growth often up to a depth of several metres (T. Saunders, pers. comm., 1988).

Toward the south, therefore, the upper part of the Wabiskaw "C" sand appears to have been deposited on or near the middle to upper shoreface, and the underlying facies, interpreted in the north as the bar margin and interbar shelf is, in the south, a true shelf to shoreface transition. As the deposits are not known to be of any economic value, no cores are available from the southernmost extent of the Wabiskaw "C" sand in Townships 72 and 73; but based on the regional evidence, it can be speculated that a shoreline or at least the transgressive erosional remnants of a shoreline may exist in that area.

Sand Transport Mechanism

A perennial problem for the recognition of shelf sands involves the source and transport mechanism required to emplace sand on a shelf. Recent studies have invoked lowstand shorelines as the possible source of sand and conglomerate in the Cardium Formation (Bergman and Walker, 1986; Plint and Walker, 1987) and the Viking Formation (Beaumont, 1984) of western Alberta. A sea-level drop would cause incision by rivers due to lowering of the base level, and would allow transport of coarse material to a newly established shoreface (Bergman and Walker, 1986).

In the Cardium Formation, a relative drop in sea level caused an erosion surface that appears to constitute a sequence boundary. In cores of the Wabiskaw "C" sand, there is no evidence of an erosion surface that would mark a lowstand of sea level, and no evidence of foreshore or emergent conditions, which one might expect if the Wabiskaw "C" sand were entirely a shoreface deposit. Lacking a more regional knowledge of the depositional systems, it may be speculated that, if the transport of the sand is indeed due to a relative sea-level drop, then the Wabiskaw "C" sand may constitute a component of an offshore, marine lowstand wedge.

The Wabiskaw "C" sand has a relatively simple geometry, and appears to be a continuous sand body. This morphology, combined with the change in environmental interpretation from north to south, strongly suggests that the Wabiskaw "C" sand is an example of a lowstand, shoreface-attached, shallow marine bar complex.

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CHAPTER VII

THE STRATIGRAPHY AND BITUMEN RESERVES OF THE WABISKAW MEMBER, CLEARWATER FORMATION, WABASCA REGION, ATHABASCA OIL SANDS

INTRODUCTION

A major portion of the bitumen reserves of the Athabasca Oil Sands in northeastern Alberta (Fig. VII-1) is contained in the Lower Cretaceous McMurray Formation of the Mannville Group. This formation forms a complex reservoir and has been interpreted in recent studies as fluvial, estuarine and marine in nature (Pemberton *et al.*, 1982, Flach and Mossop, 1985; Fox, 1988; Keith *et al.*, 1988; Ranger and Pemberton, 1988). Its lithologic complexity makes it a difficult target for exploitation especially in the areas too deep for surface mining where *in situ* methods will be required for extraction of the bitumen.

A lesser-known reservoir unit in the western part of the Athabasca Deposit is the Wabiskaw Member of the Clearwater Formation, also in the Mannville Group, and immediately overlying the McMurray Formation (Fig. VII-2). Although proven in-place bitumen reserves are much smaller in the Wabiskaw Member (26×10^9 bbls > 5 wt%: ERCB, 1976) than in the McMurray Formation, a simpler and therefore more predictable reservoir geometry makes the Wabiskaw Member an attractive candidate for *in situ* bitumen recovery schemes. The bitumen lies trapped at depths ranging from about 300 m in the northeast to about 800 m in the southwest. These depths are well beyond the economic limits of surface mining, and therefore successful exploitation will require *in situ* techniques to heat and mobilise the bitumen so that it can be pumped to the surface.

Wabiskaw nomenclature can be confusing, particularly the variations in spelling in use in the study area. The stratigraphic term "Wabiskaw Member" originated from the Barnsdall West Wabiskaw No. 1 well drilled in September, 1949. However, geographic names in the area use the spelling

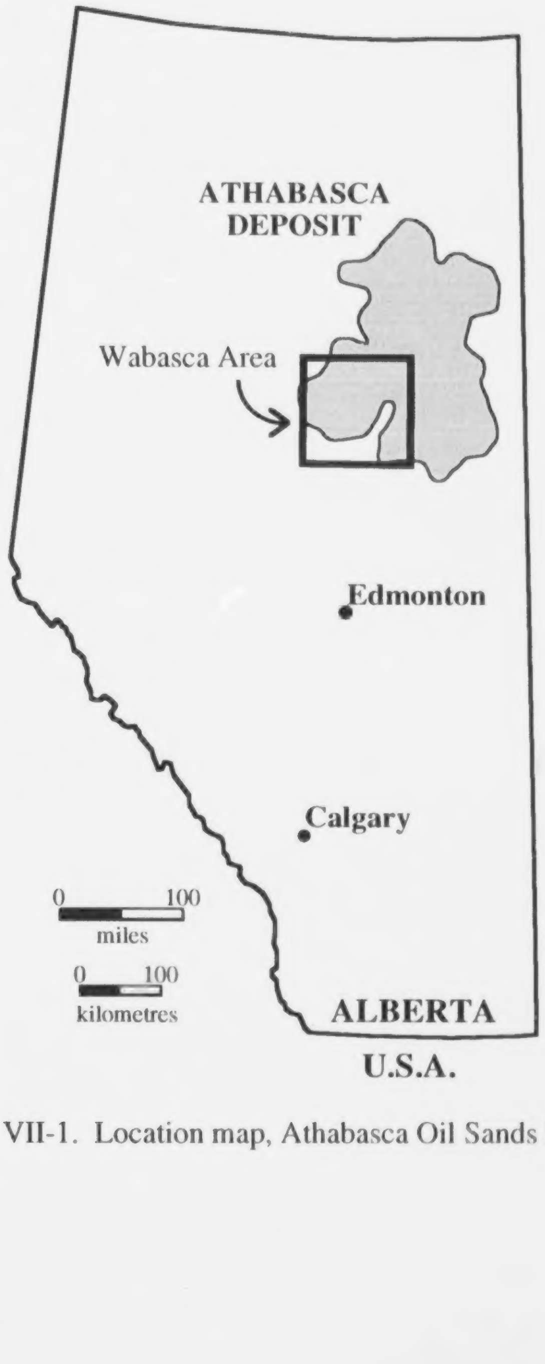
ATHABASCA DEPOSIT
Wabasca Area
Edmonton
Calgary
0 100
miles
0 100
kilometres
ALBERTA
U.S.A.

Figure VII-1. Location map, Athabasca Oil Sands Deposit

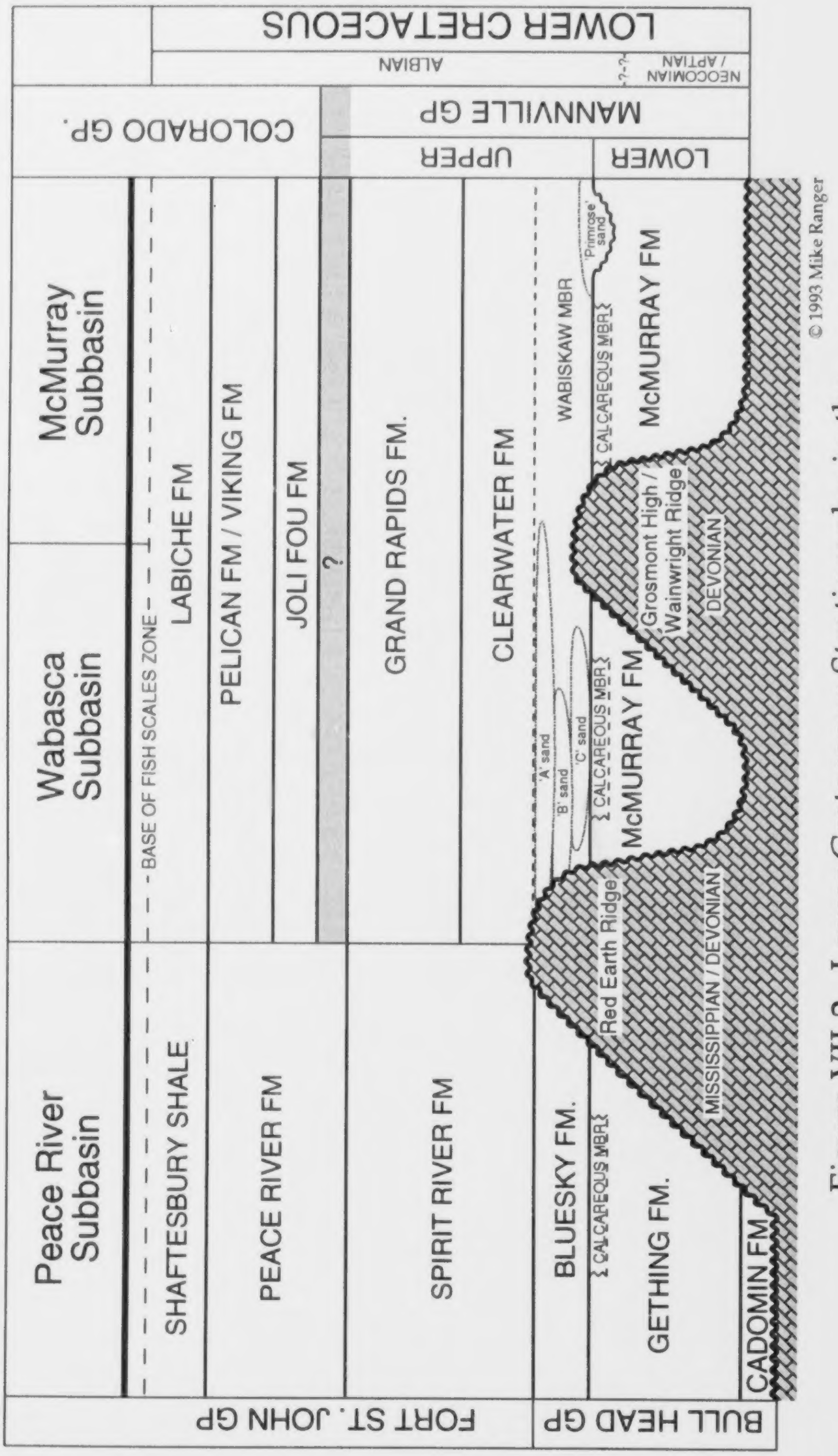
LOWER CRETACEOUS
ALBIAN
NEOCOMIAN / APTIAN
COLORADO GP.
MANNVILLE GP
UPPER
LOWER
FORT ST. JOHN GP
BULL HEAD GP
Peace River Subbasin
Wabasca Subbasin
McMurray Subbasin
BASE OF FISH SCALES ZONE
SHAFTESBURY SHALE
LABICHE FM
PEACE RIVER FM
PELICAN FM / VIKING FM
JOLI FOU FM
?
SPIRIT RIVER FM
GRAND RAPIDS FM.
CLEARWATER FM
BLUESKY FM.
WABISKAW MBR
'A' sand
'B' sand
'C' sand
'Primrose' sand
CALCAREOUS MBR
GETHING FM.
McMURRAY FM
CADOMIN FM
Red Earth Ridge
Grosmont High / Wainwright Ridge
MISSISSIPPIAN / DEVONIAN
DEVONIAN

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Figure VII-2. Lower Cretaceous Stratigraphy in the McMurray, Wabasca and Peace River Subbasins.

"Wabasca". Furthermore, a separate occurrence of oil sands overlying the Athabasca Deposit is known as the "Wabasca Oil Sands Deposit". As originally recognised by the Alberta Energy Resources Conservation Board, the Wabasca Deposit included the oil sands of the Wabiskaw Member (Wabasca "B" deposit) as well as oil sands occurring in the overlying Grand Rapids Formation (Wabasca "A" deposit). This designation has subsequently been amended so that oil sands of the Wabiskaw Member are now included in the Athabasca Deposit, and the Wabasca Deposit includes only the oil sands of the Grand Rapids Formation. In this study the term "Wabiskaw" Member is used as the lithostratigraphic reference, while "Wabasca" is used occasionally to refer to the geographic region that includes the study area. References to the Athabasca Deposit thus include the oil sands of the Wabiskaw Member in the Wabasca area.

The purpose of this study is to outline the stratigraphy, sedimentology and regional geometry of the Wabiskaw Member as well as to characterise the distribution of its hydrocarbon resources. This study extends the published knowledge on the Wabiskaw by delineating and mapping each of three constituent sand bodies individually, describing their three-dimensional geometry, showing their position in the subbasin, describing the spatial distribution of their lithofacies and ichnofacies, and providing a interpretation of their origin.

The study area encompasses townships 70 to 84 and ranges 16W4 to 5W5, an area of over 23,000 square kilometres. In this area the Wabiskaw Member occurs in the subsurface only. It does crop out in the Fort McMurray area, 60 km to the east, but in a different subbasin. The project database consists of geophysical logs from approximately 750 wells, and of these the Wabiskaw Member has been cored at least partially in about 150 wells. Eighteen of these cores were studied in detail, the others being extremely rubbly or of rather limited penetration. Several areas such as the Pelican pilot site in township 81, range 22W4, presently operated by CS Resources, have many closely spaced cored wells, on the order of several hundred metres apart, and examining more than one or two cores from these facilities would provide no additional useful information. Facies and facies successions do not differ dramatically from well to well over the whole of the study area.

In the study area the Wabiskaw Member consists of three major sheet-like units that coarsen upwards from shale to fine sand. These three units are informally referred to, from the top downwards, as: the Wabiskaw "A" sand, the Wabiskaw "B" sand and the W abiskaw "C" sand. The three units are separated from each other by shales and each has proven to be correlatable and mappable over a wide area (Fig. VII-3), although towards the south and southwest, one or both of the intervening shales may be missing, producing amalgamated sand bodies.

STRATIGRAPHY

The term Wabiskaw Member was originally coined by Badgley (1952), to describe the lowermost glauconitic, sandy unit of the Clearwater Formation in northeastern Alberta. The Clearwater Formation was recognised as the deposits resulting from the first major marine transgression of the Early Cretaceous in the area, and the sands of the Wabiskaw Member were believed to be the initial transgressive reworking of underlying McMurray Formation sediments. The base of the Wabiskaw Member, and therefore the Clearwater Formation is recognised by the abrupt appearance of abundant glauconite in the sediment (Carrigy, 1963). This contact is usually readily recognisable in cores from the study area, but picking the contact from geophysical logs is less reliable. On geophysical logs the contact can sometimes be picked because the lithofacies of the McMurray are complex and change rapidly both vertically and laterally, whereas the development of the Wabiskaw sands is more uniform and predictable from well to well.

Correct stratigraphic nomenclature used to describe the separate sand units recognised in the Wabiskaw Member is difficult to apply. Each of the sand bodies and associated underlying shales in the study area meet the criteria for member status: lithologically they are independently developed and, for the most part, individually correlatable and mappable. Giving each member status would necessitate either raising the Wabiskaw Member to formation status, or discarding the term altogether. The Wabiskaw Member,

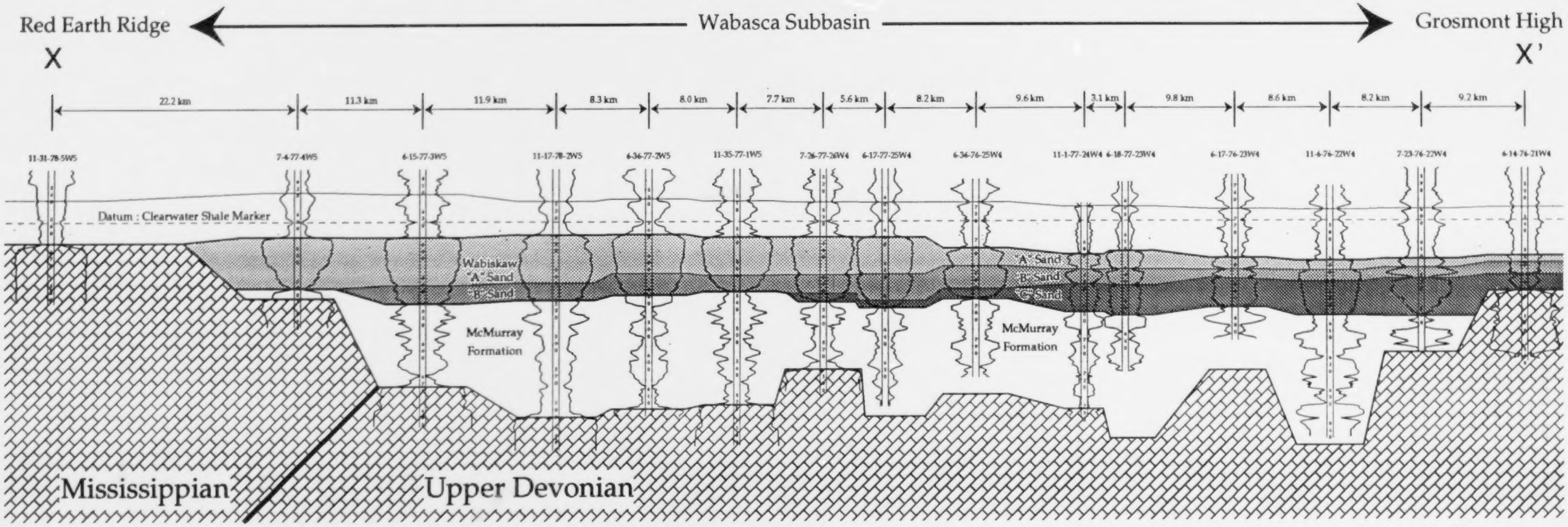
Red Earth Ridge
Wabasca Subbasin
Grosmont High
X
X'
22.2 km
11.3 km
11.9 km
8.3 km
8.0 km
7.7 km
5.6 km
8.2 km
9.6 km
3.1 km
9.8 km
8.6 km
8.2 km
9.2 km
11-31-78-5W5
7-4-77-4W5
6-15-77-3W5
11-17-78-2W5
6-36-77-2W5
11-35-77-1W5
7-26-77-26W4
6-17-77-25W4
6-36-76-25W4
11-1-77-24W4
6-18-77-23W4
6-17-76-23W4
11-6-76-22W4
7-23-76-22W4
6-14-76-21W4
Datum : Clearwater Shale Marker
Wabiskaw
"A" Sand
"B" Sand
"A" Sand
"B" Sand
"C" Sand
McMurray Formation
McMurray Formation
Mississippian
Upper Devonian

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Figure VII-3. East-west cross-section through the Wabiskaw sands in the Wabasca area. Geophysical logs are gamma-ray response, with right track reversed.

as presently defined, is the lithostratigraphic equivalent of the Glauconitic Sandstone in southern Alberta, the Bluesky Formation of the Peace River Area, and the Cummings Formation of the Lloydminster area (Kramers, 1990), and could conceivably be raised to formation status, independent of the Clearwater Formation. However the term Wabiskaw Member is in common use and in fact use of the term Wabiskaw Member extends much further beyond the mapped geographic extent of the three sands in the study area. For instance, in the Fort McMurray area, in a different subbasin, the Wabiskaw is widely recognised as a member of the Clearwater Formation, although it has not been further subdivided.

Therefore, the recognition of three component units in a minor portion of its geographic area is not considered sufficient justification for giving the Wabiskaw Member formational status. The problem of the status of the three units thus remains. They are not "beds" in that they are not unit layers, and are about two orders of magnitude thicker than what would customarily be considered a bed. The informal terms "zone" (i.e. lithozone) or "lens" also seem inappropriate. It appears sufficient for the present to let the nomenclature remain on informal status, as the Wabiskaw "A" sand, Wabiskaw "B" sand and Wabiskaw "C" sand. The term sand (uncapitalised) is considered herein as an informal lithostratigraphic term, which, in conformance with codes of stratigraphic nomenclature, can be used to describe a lithologic body for which there is insufficient need to justify designation as a formal unit. It may be argued that the term "sand" may not be entirely suitable, since it is commonly used as the descriptive lithologic part of a formal lithostratigraphic name. However when used as part of a formal name it must always be capitalised.

In the subsurface, the Wabiskaw Member was first recognised in the West Wabiskaw No. 1 well, located at 11-17-78-2W5 (Badgley, 1952). By priority therefore, the interval in this well is to be considered the stratotype. However the core recovered from this well is a small diameter wireline core and is in extremely poor condition. The geophysical logs are dated and of poor quality. Furthermore, this well is not ideally situated to show the typical development of all three component sands. It is proposed, therefore that another well, Pan Am C-1 Rock located at 6-18-77-23W4 be designated a reference section (hypostratotype) for the Wabiskaw Member in the Wabasca area. This well, drilled in 1969, has a full suite of modern geophysical logs, and core penetrates, at least partially, all three component sands, as well as the contact with the underlying McMurray Formation. Furthermore, the well is located where all three sand bodies overlap, are separated by shales, and are more or less equally well-developed. This well therefore is in a key location for recognising and correlating the three sand units. One other nearby well, 11-1-77-24W4, also penetrates the three sands where they are similarly developed and easily recognised. Although this well has somewhat more core coverage over the Wabiskaw interval, the core is rubbly and poorly preserved. Figure VII-4 shows the proposed hypostratotype well, describing it graphically, and figure VII-5 demonstrates its lithostratigraphic relationship with the stratotype well using a geophysical log cross-section.

REGIONAL BASIN PALEOGEOGRAPHY

The Wabiskaw Member is normally separated from a major regional unconformity, the sub-Cretaceous unconformity, by the fluvial to marginal marine McMurray Formation, which appears to be a valley-fill sequence on the unconformity. However in several wells in the south of the study area, the McMurray Formation is missing and the Wabiskaw Member lies directly on the sub-Cretaceous unconformity. This suggests that the morphology of the drainage valley system expressed as the sub-Cretaceous unconformity must have played some role in the accumulation and geometry of the Wabiskaw sand bodies. The morphology of the sub-Cretaceous unconformity has been mapped using the isopach of the Mannville Group (Ranger, 1984). Making the assumption that the top of the Mannville group (base of the Joli Fou shale) was approximately a flat surface (i.e. parallel to paleo-sea level) at the time of deposition, then the thickness of the Mannville Group represents a "mould" of the sub-Cretaceous unconformity on which it lies. This can only be considered an approximation since other processes such as differential compaction due to variations in thickness or lithology can have a subtle but recognisable effect. In this study the top of the lower Mannville

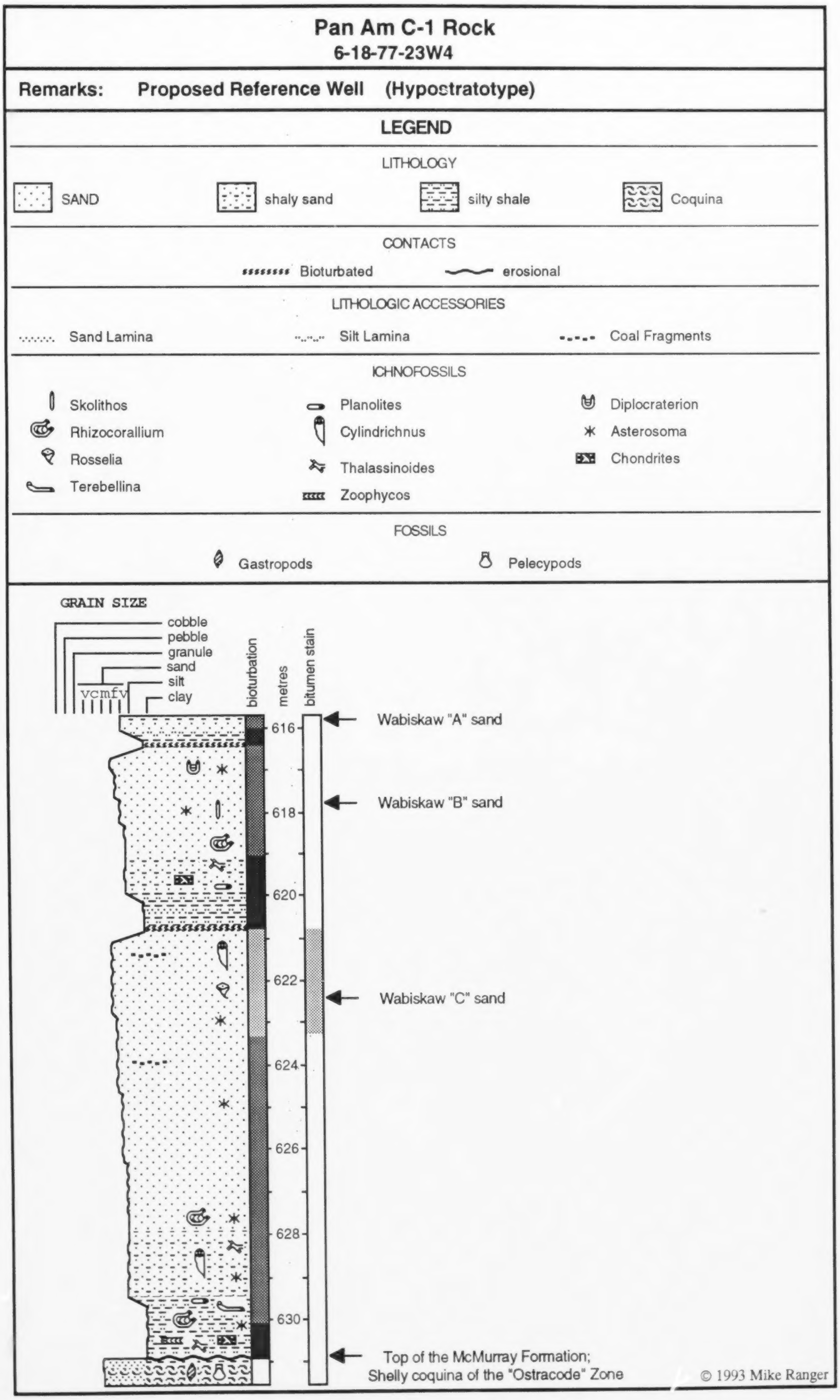

Pan Am C-1 Rock
6-18-77-23W4
Remarks: Proposed Reference Well (Hypostratotype)
LEGEND
LITHOLOGY
SAND
shaly sand
silty shale
Coquina
CONTACTS
Bioturbated
erosional
LITHOLOGIC ACCESSORIES
Sand Lamina
Silt Lamina
Coal Fragments
ICHNOFOSSILS
Skolithos
Rhizocorallium
Rosselia
Terebellina
Planolites
Cylindrichnus
Thalassinoides
Zoophycos
Diplocraterion
Asterosoma
Chondrites
FOSSILS
Gastropods
Pelecypods
GRAIN SIZE
cobble
pebble
granule
sand
silt
clay
vcmfv
bioturbation
metres
bitumen stain
616
618
620
622
624
626
628
630
Wabiskaw "A" sand
Wabiskaw "B" sand
Wabiskaw "C" sand
Top of the McMurray Formation;
Shelly coquina of the "Ostracode" Zone
© 1993 Mike Ranger

Figure VII-4. Sedimentological description of 6-18-77-23W4: the proposed reference section or "hypostratotype".

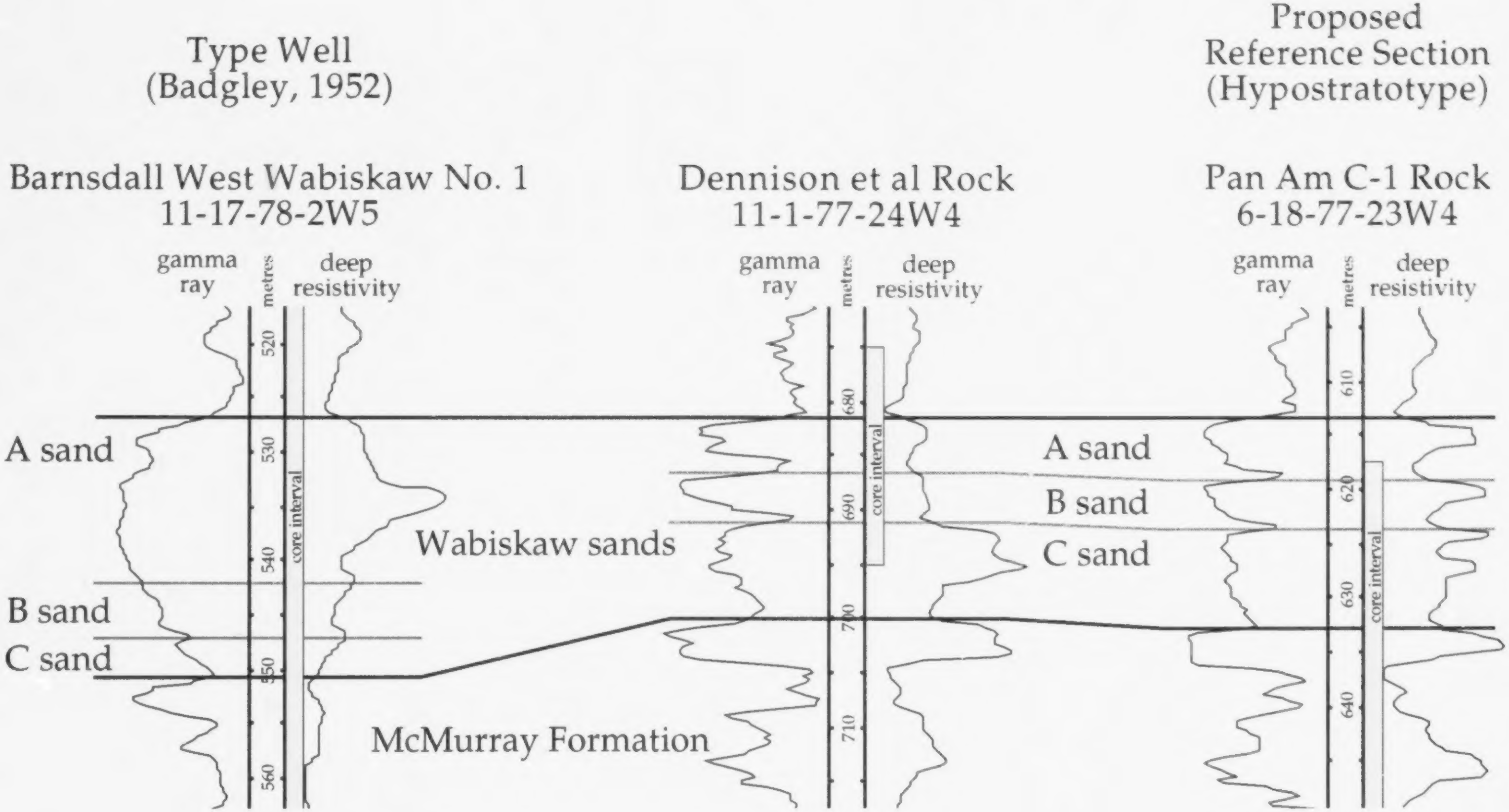

Type Well
(Badgley, 1952)
Proposed
Reference Section
(Hypostratotype)
Barnsdall West Wabiskaw No. 1
11-17-78-2W5
Dennison et al Rock
11-1-77-24W4
Pan Am C-1 Rock
6-18-77-23W4
gamma ray
metres
deep resistivity
core interval
520
530
540
550
560
680
690
700
710
610
620
630
640
A sand
B sand
C sand
Wabiskaw sands
McMurray Formation

Figure VII-5. Cross-section through type well 11-17-78-2W5 and proposed reference well 6-18-77-23W4

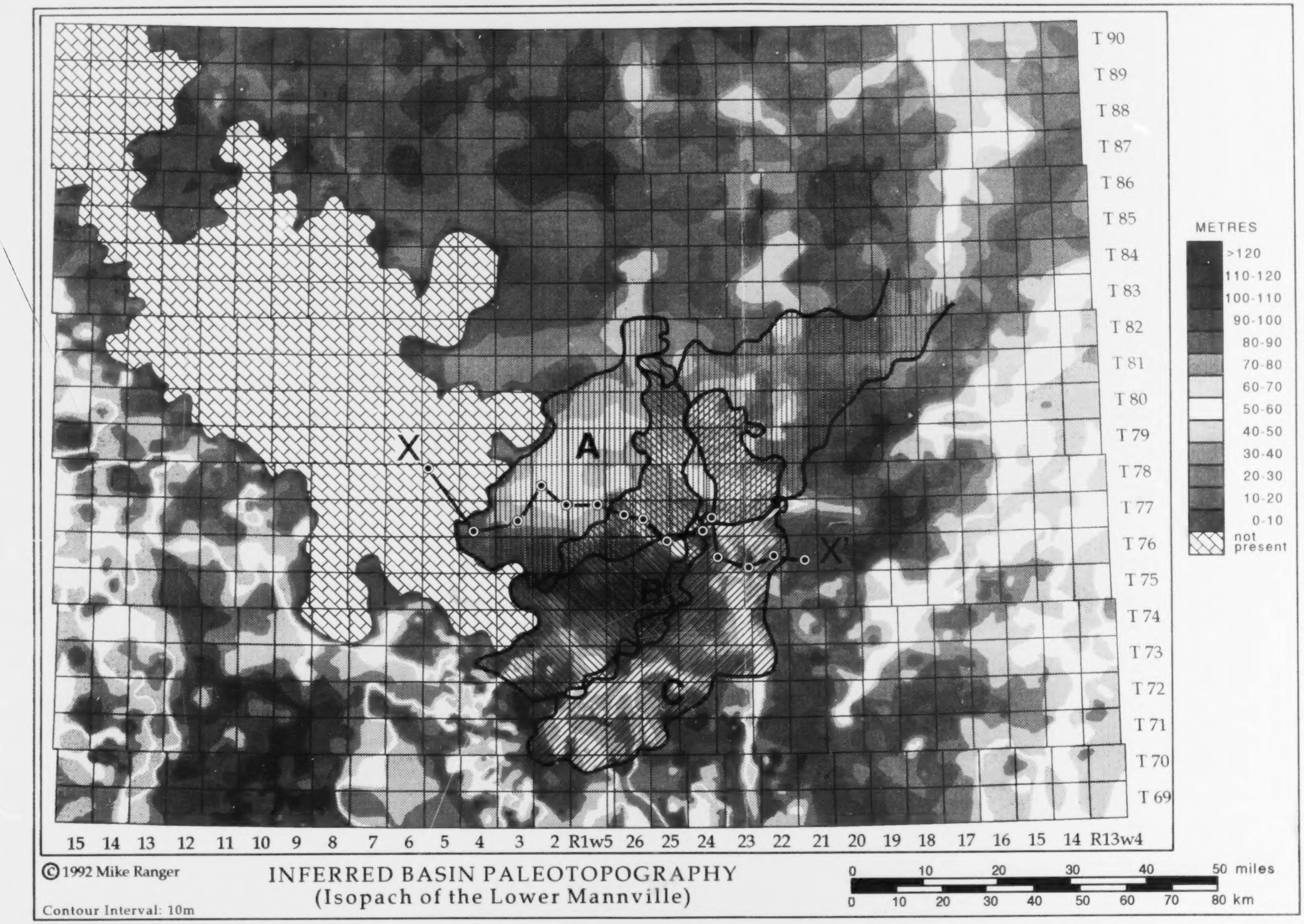
Group is used as an upper marker for an isopach map, because the top of the Mannville Group is eroded toward the shallow northeast. The isopach map provides a perspective of the regional basin setting of the Wabiskaw sand bodies (Fig. VII-6).

It appears that during Early Cretaceous time, the Wabasca area lay between two major trunk valley systems on the sub-Cretaceous unconformity, the Edmonton Channel valley system (Williams, 1963) on the west and the informally named McMurray Channel valley system on the east (Ranger 1984). The Wabasca area appears to have been a small subbasin herein termed the Wabasca subbasin, which is bordered on the east by a resistant ridge of Devonian carbonate, an extension of what is known as the Grosmont High. To the west is a little-known resistant ridge of Mississippian carbonate, the Banff Formation, herein referred to as the Red Earth Ridge. It appears as if the Wabasca subbasin drained southward into the Edmonton Channel valley system through a rather narrow valley cut into the Paleozoic surface in the south of the subbasin. An alternate interpretation is that the southern border of the subbasin is the headwaters of the local drainage system, and the subbasin drained northwards, perhaps into the boreal sea as an independent drainage system, or eventually circumventing the Red Earth Ridge to the west, and joining the Edmonton Channel valley system as a major tributary. Well data is as yet too sparse in the northern areas to confirm the topography.

Figure VII-6 demonstrates the geographic position of all three sand bodies relative to underlying paleotopography on the sub-Cretaceous unconformity. They lie over the southern to south-southwestern flank of the Wabasca subbasin, extending into its axis and, in the case of the Wabiskaw "A" sand, continuing up the flank on the northeastern side.

Note in particular the relationship of the position of the Wabiskaw "C" sand to the underlying paleotopography. It directly overlies the narrow, steep valley, providing evidence that the valley controlled the deposition of the sand (Ranger *et al.*, 1988).

Figure VII-6. Isopach map of the Lower Mannville Group of northeastern Alberta representing the erosional topography on the sub-Cretaceous unconformity. Brickwork pattern represents non-deposition of the Lower Mannville (and the Wabiskaw Member) indicating a paleotopographic high or "island" during marine transgression. Gray cross-hatched outlines are the 4 metre contour limits of the Wabiskaw "A", "B" and "C" sands from northwest to southeast respectively. Line X-X′ refers to cross-section figure VII-3.



INFERRED BASIN PALEOTOPOGRAPHY
(Isopach of the Lower Mannville)

T 90
T 89
T 88
T 87
T 86
T 85
T 84
T 83
T 82
T 81
T 80
T 79
T 78
T 77
T 76
T 75
T 74
T 73
T 72
T 71
T 70
T 69
15 14 13 12 11 10 9 8 7 6 5 4 3 2 R1w5 26 25 24 23 22 21 20 19 18 17 16 15 14 R13w4
X
A
B
C
X'
METRES
>120
110-120
100-110
90-100
80-90
70-80
60-70
50-60
40-50
30-40
20-30
10-20
0-10
not present
0 10 20 30 40 50 miles
0 10 20 30 40 50 60 70 80 km
Contour Interval: 10m

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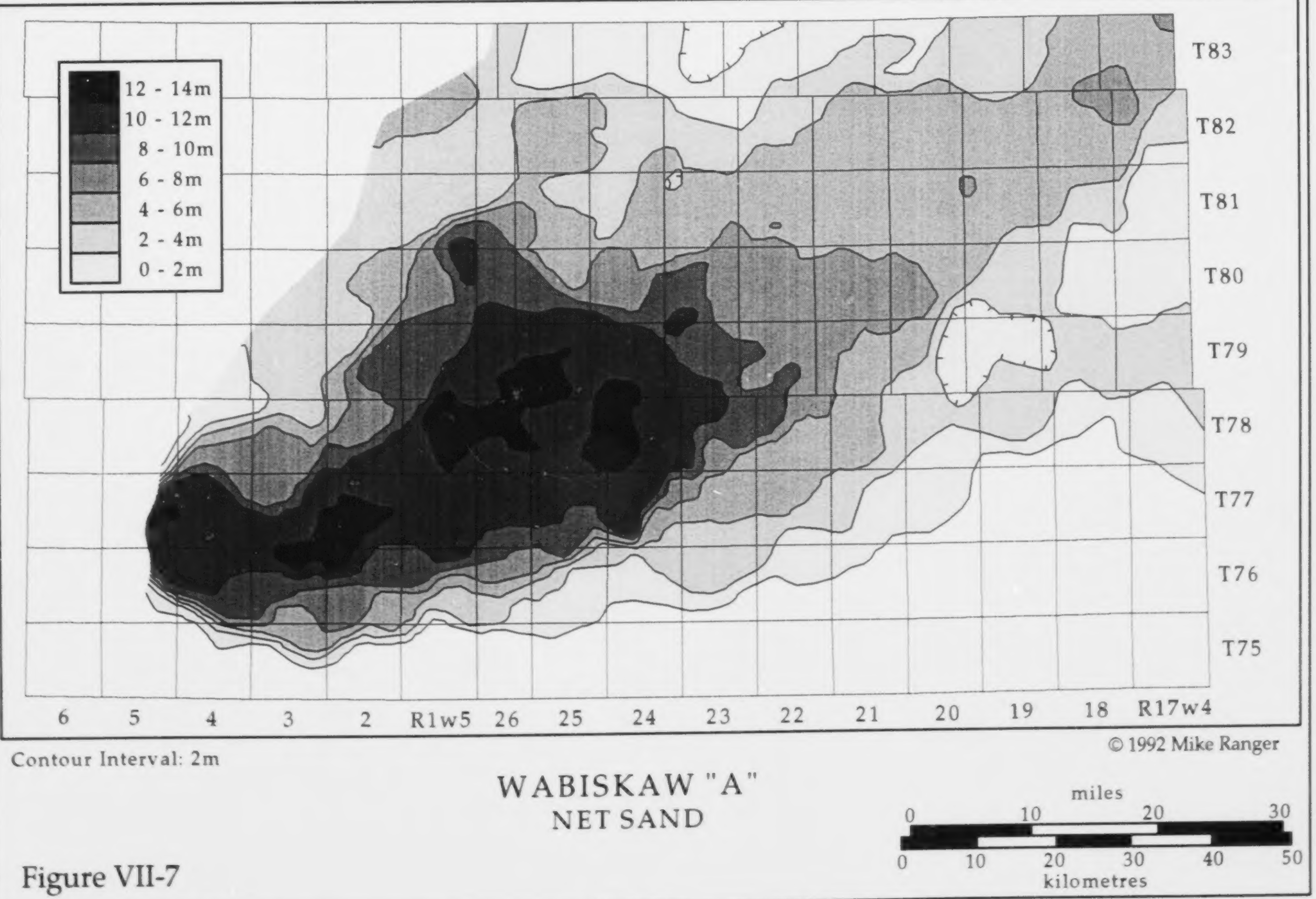
GEOMETRY OF THE SAND BODIES

The development of the three sand bodies in the Wabiskaw Member can be mapped using geophysical logs. A 50% response cutoff of the gamma-ray curve can be used to map the geometry of each sand (Figs. VII-7, VII-8 and VII-9). The sand bodies all have a elongated, partially lobate morphology with an orientation of north-northeast – south-southwest for the Wabiskaw "C" and Wabiskaw "B" sands, and northeast – southwest for the Wabiskaw "A" sand. Morphologically all three appear to have a somewhat simple makeup, that of rather subtle and gradual development into relatively thin but areally large sand bodies enclosed in shales. Toward the south and southeast, intervening shales are commonly absent, producing amalgamated sand bodies, which can be difficult to differentiate in well logs and core. Each of the three sand bodies is 6000-7000 square kilometres in area, but averages only about 10 to 12 metres in thickness. Maximum thickness is in the southern part of the Wabiskaw "C" sand, where it reaches 20 metres. More typical, however, is in the area of the CS Resources Pelican site in township 81, range 22W4, where the Wabiskaw "A" sand is the best developed of the three, averaging about 5 m in thickness. Thicker sands also commonly extend down into an underlying water zone.

Another aspect of note concerning the geometry of the sand bodies is that the edges of the sand bodies have different thickness gradients on opposite sides. For instance, both the Wabiskaw "A" and the Wabiskaw "B" sands have a steeper thickness gradient on their southeastern margin than on the northwestern side (Figs. VII-7 and VII-8). To the northeast the sand pinchout is so gradual that a definite edge is not seen and sand persists beyond the study area. The Wabiskaw "B" sand appears to have developed in two distinct thickness maxima, with a smaller body to the northwest of the major buildup, and separated by a thinning "saddle". Over the saddle, the shale separating the Wabiskaw "A" from the Wabiskaw "B" is missing, producing an amalgamated sand. The nature and exact position of the contact is not obvious from logs or core. Its position in wells where the sands are amalgamated is interpolated from surrounding well data. The thin saddle apparently results from erosional scour during transgression after


12 - 14m
10 - 12m
8 - 10m
6 - 8m
4 - 6m
2 - 4m
0 - 2m
T83
T82
T81
T80
T79
T78
T77
T76
T75
6
5
4
3
2
R1w5
26
25
24
23
22
21
20
19
18
R17w4
Contour Interval: 2m
© 1992 Mike Ranger
miles
0
10
20
30
0
10
20
30
40
50
kilometres

WABISKAW "A"
NET SAND

Figure VII-7

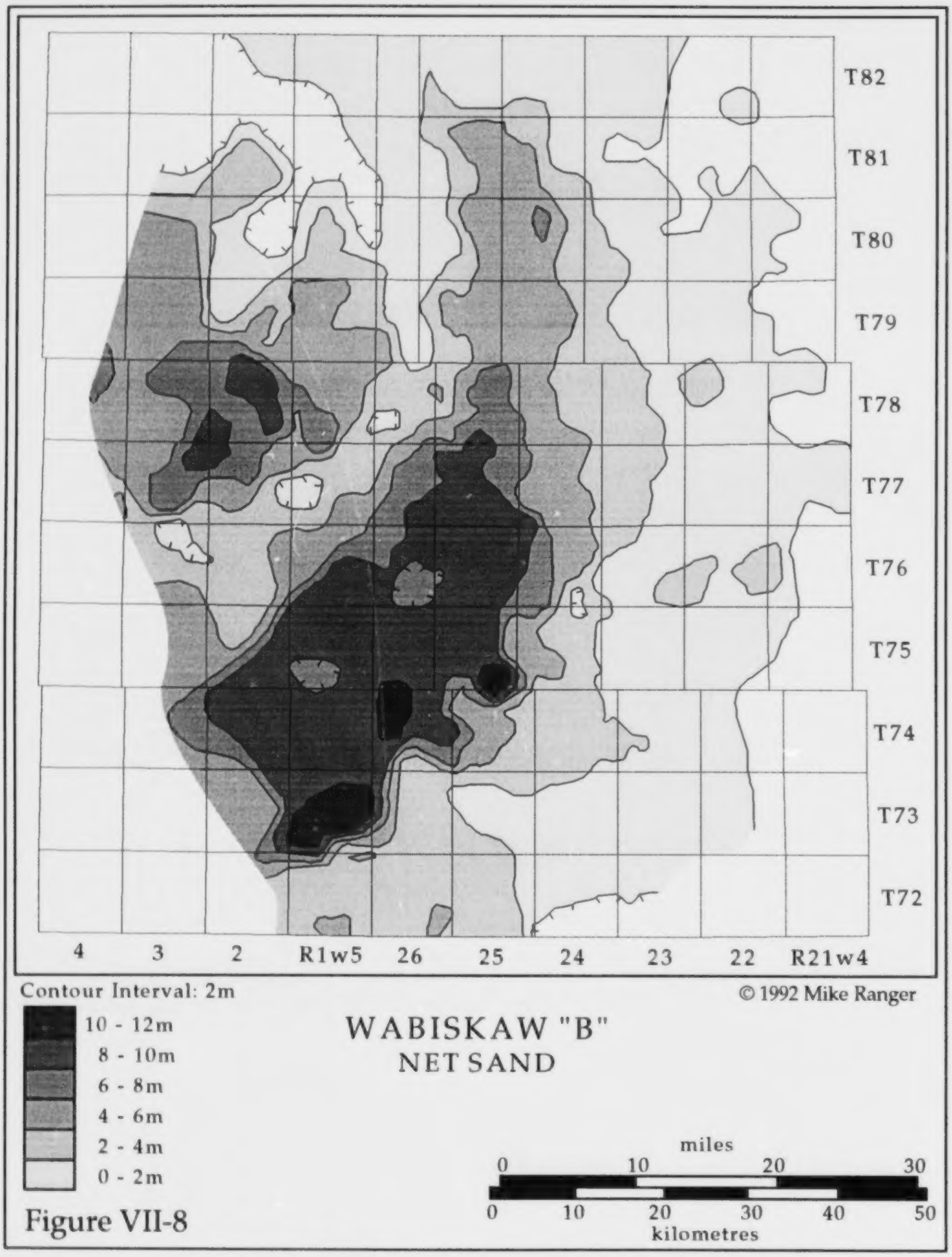
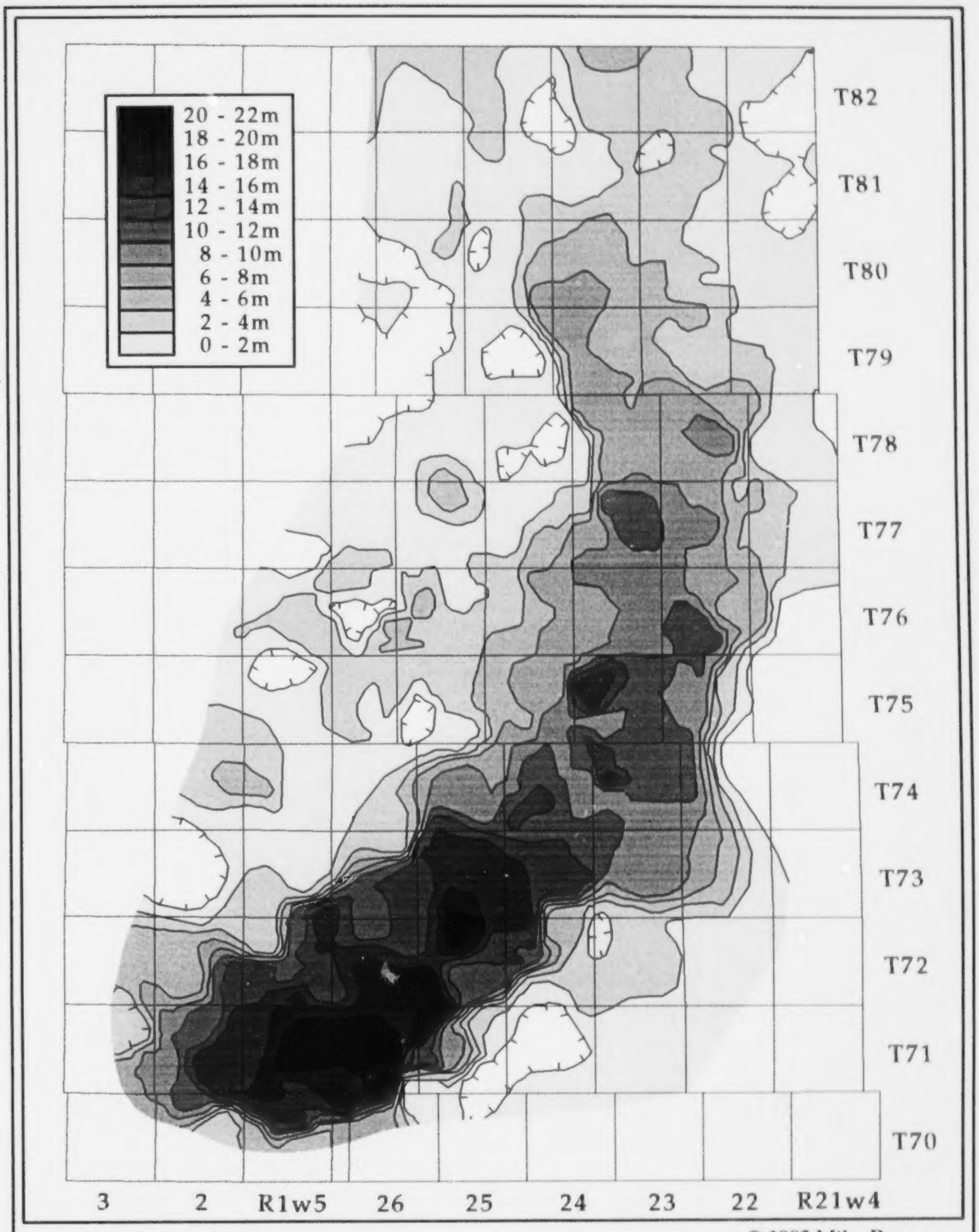

T82
T81
T80
T79
T78
T77
T76
T75
T74
T73
T72
4
3
2
R1w5
26
25
24
23
22
R21w4
Contour Interval: 2m
© 1992 Mike Ranger
10 - 12m
8 - 10m
6 - 8m
4 - 6m
2 - 4m
0 - 2m
WABISKAW "B"
NET SAND
miles
0
10
20
30
0
10
20
30
40
50
kilometres

Figure VII-8


20 - 22m
18 - 20m
16 - 18m
14 - 16m
12 - 14m
10 - 12m
8 - 10m
6 - 8m
4 - 6m
2 - 4m
0 - 2m
T82
T81
T80
T79
T78
T77
T76
T75
T74
T73
T72
T71
T70
3
2
R1w5
26
25
24
23
22
R21w4

Contour Interval: 2m

© 1992 Mike Ranger

WABISKAW "C"
NET SAND

miles
0
10
20
30
0
10
20
30
40
50
kilometres

Figure VII-9

deposition of the Wabiskaw "B" sand, or during deposition of the Wabiskaw "A" sand.

SEDIMENTOLOGY

The facies of the Wabiskaw Member in the Wabasca area are relatively few. Each of the three units become sandier upward (Fig. VII-10) and the sands become slightly coarser upward (Fig. VII-11). The relative degree of bioturbation decreases upward along with a gradual change from deposit feeding forms of the *Cruziana* ichnofacies to dominantly suspension feeding forms of the *Skolithos* ichnofacies as the units become sandier. The facies changes are generally gradual, and the exact boundaries are somewhat arbitrary. The facies and their attendant ichnofossil suites have been described in detail by Ranger *et al.* (1988) for the Wabiskaw "C" sand, but the facies for that unit persist into the Wabiskaw "B" and the Wabiskaw "A". They are summarised here only briefly.

Facies 1

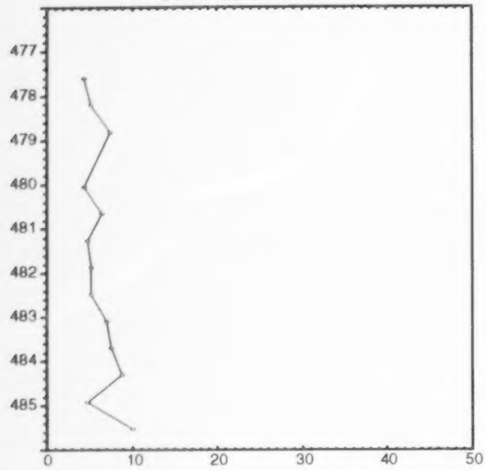
This is a fine-grained sand, coarsening upward slightly; bedding typically appears massive due to masking by bitumen saturation, but may display low angle planar cross-bedding interpreted to be hummocky cross-stratification. The ichnofossil suite is typically a low density assemblage of dwelling structures such as *Palaeophycus* and *Skolithos*, but also rare deposit feeding burrows such as *Asterosoma.*

Facies 2

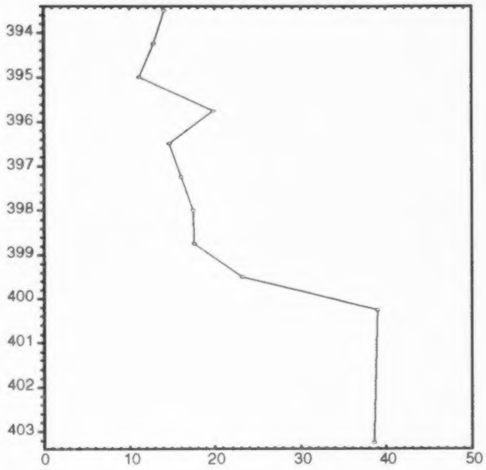
This facies reflects a slight change from facies 1. Lithologically they are similar but facies 2 is somewhat finer grained, becoming very fine grained with discrete shale beds preserved towards the base. The density and diversity of bioturbation has increased over facies 1, and the ichnofossil suite reflects an increase in deposit feeding activity with the appearance of forms such as *Teichichnus*, *Rosselia* and more abundant *Asterosoma.*

Figure VII-10. Percent shale plotted against depth: selected samples from each of the three sands. Vertical axis: metres below KB. Horizontal axis: weight percent shale.

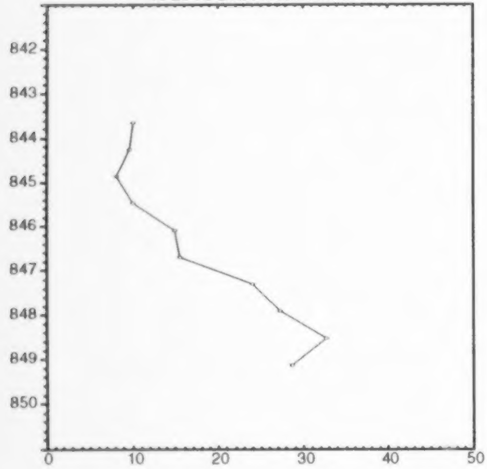
6-7-79-1w5 Wabiskaw "A"



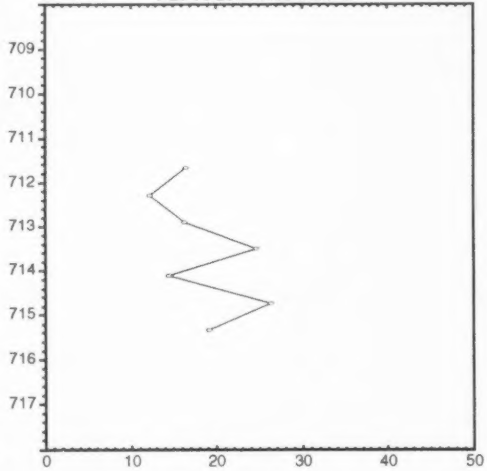
14-14-79-22w4 Wabiskaw "A"



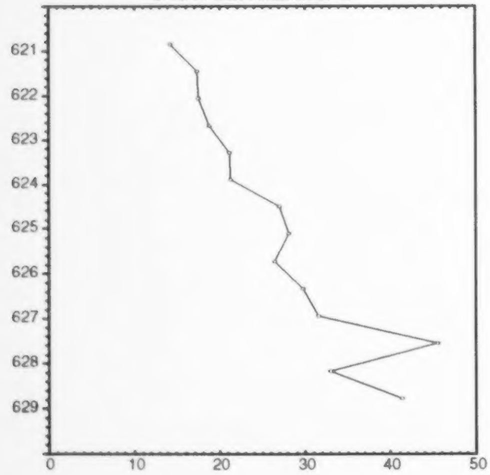
10-20-76-24w4 Wabiskaw "B"



7-25-76-26w4 Wabiskaw "B"



6-18-77-23w4 Wabiskaw "C"



11-6-76-22w4 Wabiskaw "C"

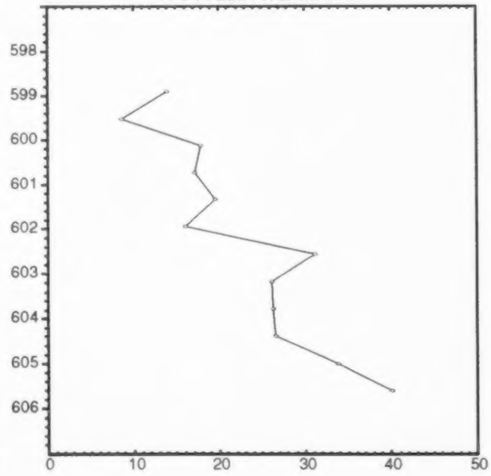
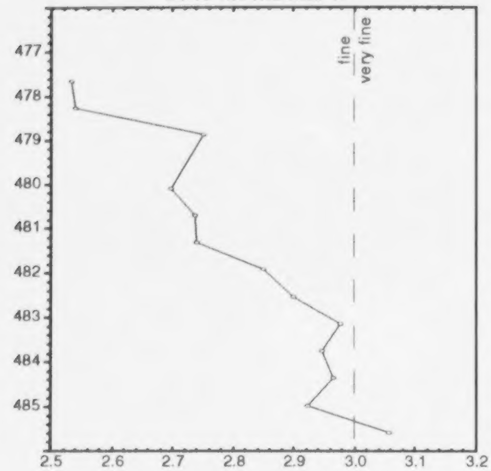
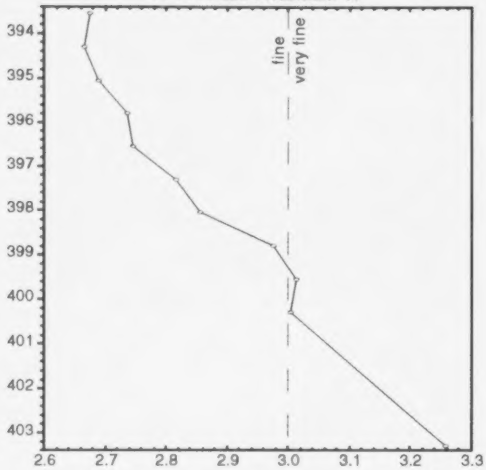


Figure VII-11. Mean sand grain size plotted against depth: selected samples from each of the three sands. Vertical axis: metres below KB. Horizontal Axis: mean grain size in phi units.

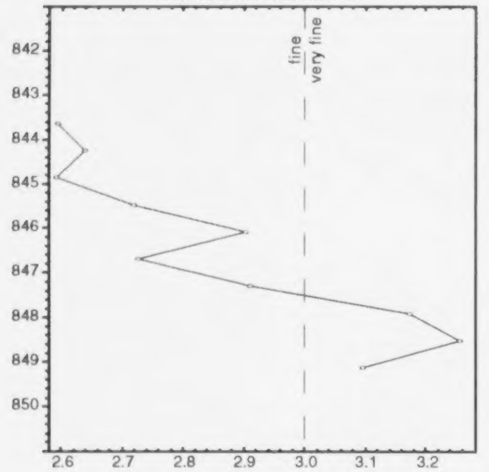
6-7-79-1w5 Wabiskaw "A"



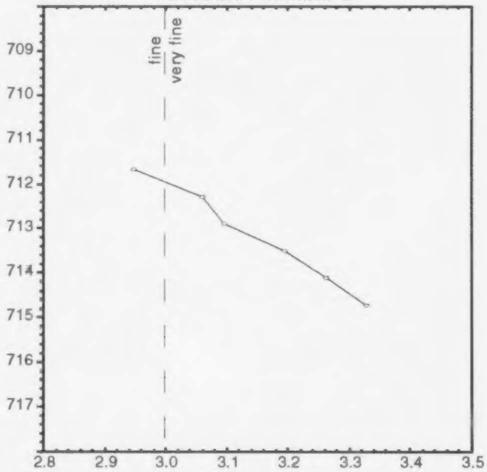
14-14-79-22w4 Wabiskaw "A"



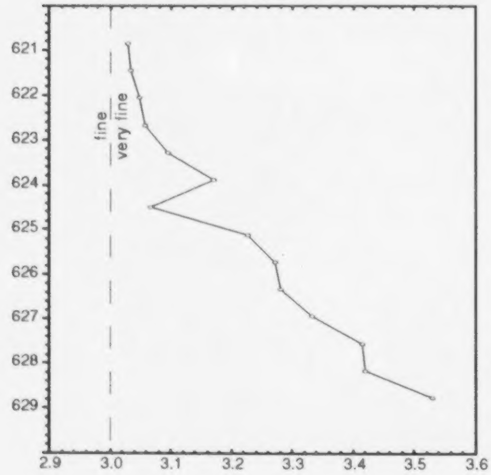
10-20-76-24w4 Wabiskaw "B"



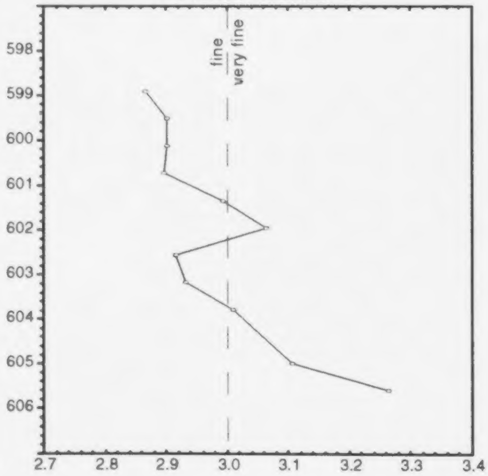
7-25-76-26w4 Wabiskaw "B"



6-18-77-23w4 Wabiskaw "C"



11-6-76-22w4 Wabiskaw "C"



Facies 3

This is a very fine-grained silty sand containing a few shell fragments. Abundant bioturbation obliterates bedding structures and is responsible for poor sorting and the clayey matrix. The ichnofossil suite contains approximately equal numbers of dwelling burrows (*Conichnus* and *Skolithos*) and feeding structures (*Asterosoma, Planolites, Chondrites* and *Teichichnus*).

Facies 4

This is an intensely bioturbated silty clay. Bedding has generally been obliterated, although rare shale laminae may be visible, and fining upwards storm beds, a few centimetres thick are occasionally observed. The ichnofossil suite is dominated by deposit feeding forms such as *Asterosoma, Teichichnus, Planolites, Chondrites, Thalassinoides, Rhizocorallium* and *Subphyllochorda* as well as grazing structures such as *Helminthopsis* and *Zoophycos*.

Facies 5

This is a medium- to fine-grained, poorly-sorted, shaly sand with some discrete shale laminae and shale lined burrows. The sand typically contains a few granules and pebbles towards the top. *Macaronichnus segregatis* is the characteristic ichnofossil throughout, as well some elements of the *Cruziana* ichnofacies such as rare *Teichichnus* burrows towards the base. This facies, where it occurs, is invariably near the top of the coarsening upwards Wabiskaw sand units.

INTERPRETATION

Almost every character of the Wabiskaw Member sands is similar to sand bodies that were historically referred to as offshore bars (Ranger, 1982). Many such examples exist in the literature especially from the western interior basin. The classic studies are those of the Shannon (Spearing,1976), Sussex (Berg, 1975), Semilla Sandstone Member of the Mancos Shale (La Fon, 1981), La Ventana Tongue (Palmer and Scott, 1984) and the Hygiene Member

(Porter, 1976) All of these sand bodies are:

1) long and linear (digitate) in three dimensional geometry;

2) encased in marine muds and are typically isolated paleogeographically many tens or hundreds of kilometres from a known penecontemporaneous continental environment;

3) sandier upwards, and the sands generally coarsen upwards, sometimes to pebbly conglomerates;

4) hummocky and swaley cross-stratified towards the top, oscillation and directional ripple bedding is rare; generally bedding is obliterated towards the muddier base due to abundant bioturbation;

5) commonly glauconitic;

6) ichnologically similar suggesting similar environmental conditions if not identical ichnofossil suites *i.e.*- fully marine conditions, with lower energy conditions towards the base supporting an abundant and diverse infaunal population, mainly deposit feeders, and higher energy storm and wave dominated conditions increasingly common upwards, supporting a moderately diverse but relatively low abundance suite of mainly suspension feeding ichnofossil forms.

The transport, emplacement and linear geometry of the sand bodies as well as the coarsening upwards concentration of sand within the sand bodies have been perpetual problems with the offshore bar model (Walker and Plint, 1992).

With the advent of the recognition of the importance of relative sea-level changes on the stratigraphic record, many of these sand bodies are being reinterpreted as lowstand shoreface deposits that form far seaward along an exposed shelf during a major sea-level fall (Bergman and Walker, 1986; Plint and Walker, 1987; Walker and Plint, 1992; Walker and Bergman, 1993). The Wabiskaw "C" sand has recently been reinterpreted as a shoreface attached sand body (Ranger *et al.*, 1988), formed during sea-level lowering.

It is suggested here that the other Wabiskaw sands, the "B" and the "A" sands also represent shoreface sands. Indeed, the facies criteria listed above as part of the characteristics of "offshore bars" are typical of shoreface deposits themselves (MacEachern and Pemberton, 1992), except that facies of the foreshore and the backshore, as well as any sign of exposure are entirely missing from the "offshore bar" deposits. None of the examined cores from any of the three sands contain facies interpreted as beach or backshore environments and non-marine indicators such as marsh coals, rootlets or paleosols have not been encountered. If these existed, they have presumably been removed by erosional scour during transgression. Sharp contacts that would indicate such erosion are likewise not in evidence. Many of the upper surfaces of the coarsening upwards sand bodies are in contact with sand of the succeeding unit, and those that are not are obscured by intense bioturbation from overlying lower shoreface shales. This character is common to all other examples of "offshore bars" and indeed the lack of exposure features is one of the main criteria that has led previous investigators to promote the interpretation of these sand bodies as shoreface detached sand bodies. Current studies in sequence stratigraphy would predict that the uppermost shoreface and the non-marine parts of a lowstand shoreface would have a very low preservation potential. It may be that, especially in the northeast, only the lower to middle shoreface ever existed, and the equivalent to a flooding surface is represented only by a change to deeper water facies. The hummocky, swaley cross-stratification, the sandier upwards nature and the ichnofossil assemblages are all typical of wave and storm dominated shoreface deposits recognised in the ancient record (MacEachern and Pemberton, 1992). The presence of glauconite implies very slow, and relatively quiet depositional conditions, interrupted only periodically by high energy, probably storm events (Ranger *et al.*, 1988).

There is additional evidence that the Wabiskaw sands represent shoreface deposits. Mapping has shown that the Wabiskaw sand bodies lie off the southeastern end of a large exposure of Mississippian outcrop that was apparently exposed during deposition of the Wabiskaw, given that no Lower Mannville sediments are preserved above it (Fig. VII-6). This was apparently a large "island" during the early Clearwater transgressions, and the juxtaposition of the three sands roughly parallel to the strike of the paleoshoreline strongly suggests that the Wabiskaw sands represent remnants of a shoreface and shallow offshore surrounding this large island.

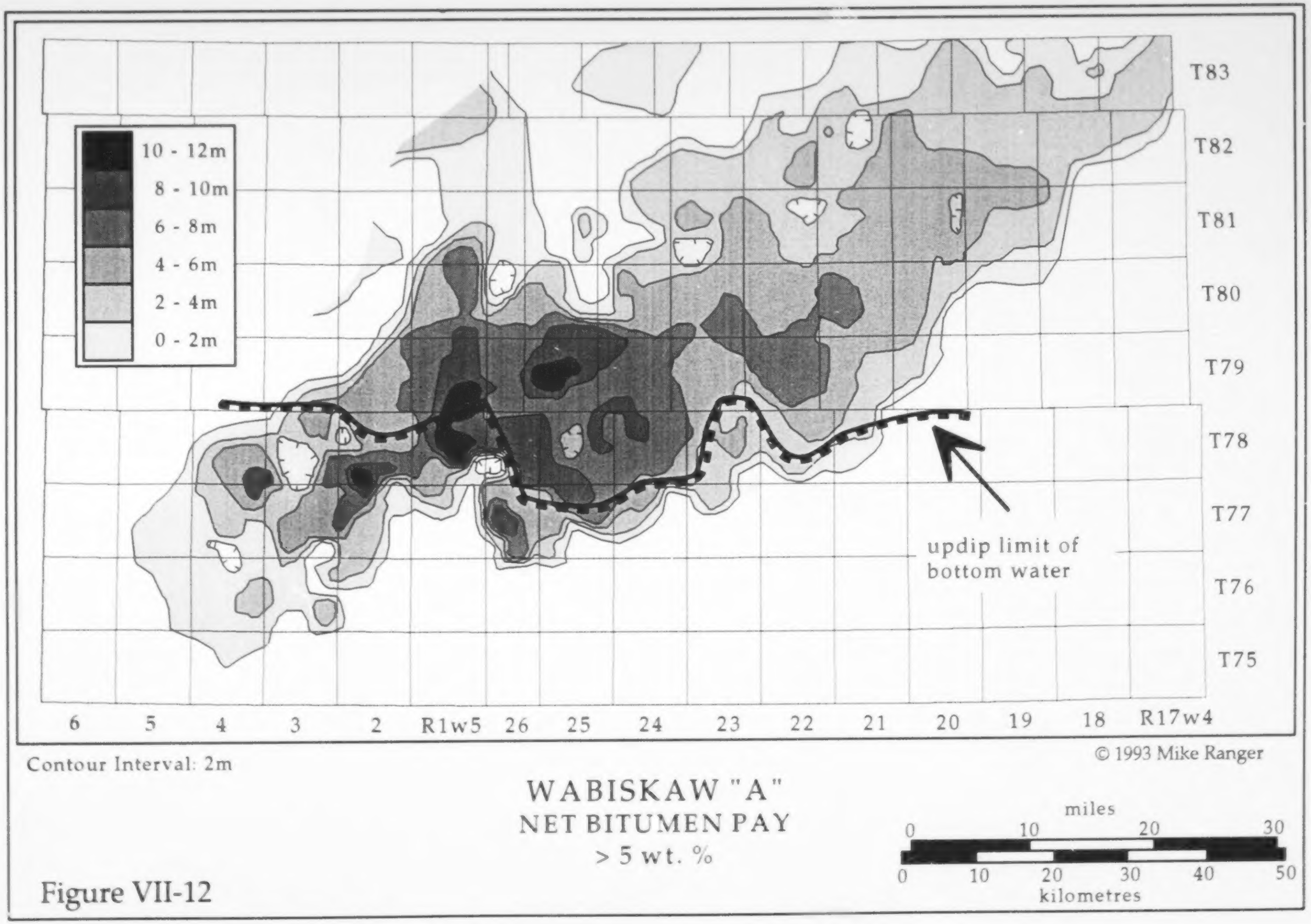
In the case of the western edge of the Wabiskaw "A" sand, it can be predicted that the sand may lie directly on the subcropping Mississippian carbonates. This has not been encountered in any wells either from core or from well logs, because the western edge of the sand has not been drilled (it lies beyond the bitumen saturated zone). The Wabiskaw "C" and "B" does lie directly in contact with the underlying Mississippian carbonates around the Marten Hills high in township 76, range 24W4.

Notice also in figure VII-6 that the successively younger sand bodies "C" to "B" to "A" are also successively closer to the island, in effect onlapping the shoreline. This is especially striking for the "B" and "C" sands, which are essentially parallel. Again this is exactly the configuration one would expect of lowstand shoreface sands in an overall transgressive system. Also, all three of the sands are thickest towards the southwest and thin gradually towards the northwest along their linear strike, suggesting longshore drift around the southeastern tip and up the leeward side of the island from a western source, possibly driven by prevailing winds and storms from the west.

HYDROCARBON RESOURCES

Each of the three sand bodies contains bitumen reserves (Figs. VII-12, VII-13 and VII-14), and each can be considered as a separate reservoir, being separated by shales in their updip positions. They do, however, merge in many places where the sands are amalgamated because intervening shales are missing. Previously, the reserves from all three sands were mapped as a unit (ERCB, 1976), and it was difficult to make sense of the distribution pattern of the bitumen and the underlying water zones. With the mapping and differentiation of the sands into three discrete reservoirs, order is brought to an otherwise obscure pattern, and useful observations may now be made regarding the trapping mechanisms, the distribution of the water zones, and the areal extent of the reserves.

By far the largest bitumen reserves are in the uppermost Wabiskaw "A" sand. Each of the reservoirs also has a discrete downdip water leg. In the Wabasca area, the Lower Mannville dips regionally towards the southwest at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19
18
R17w4
updip limit of bottom water
miles
0
10
20
30
0
10
20
30
40
50
kilometres

Contour Interval: 2m

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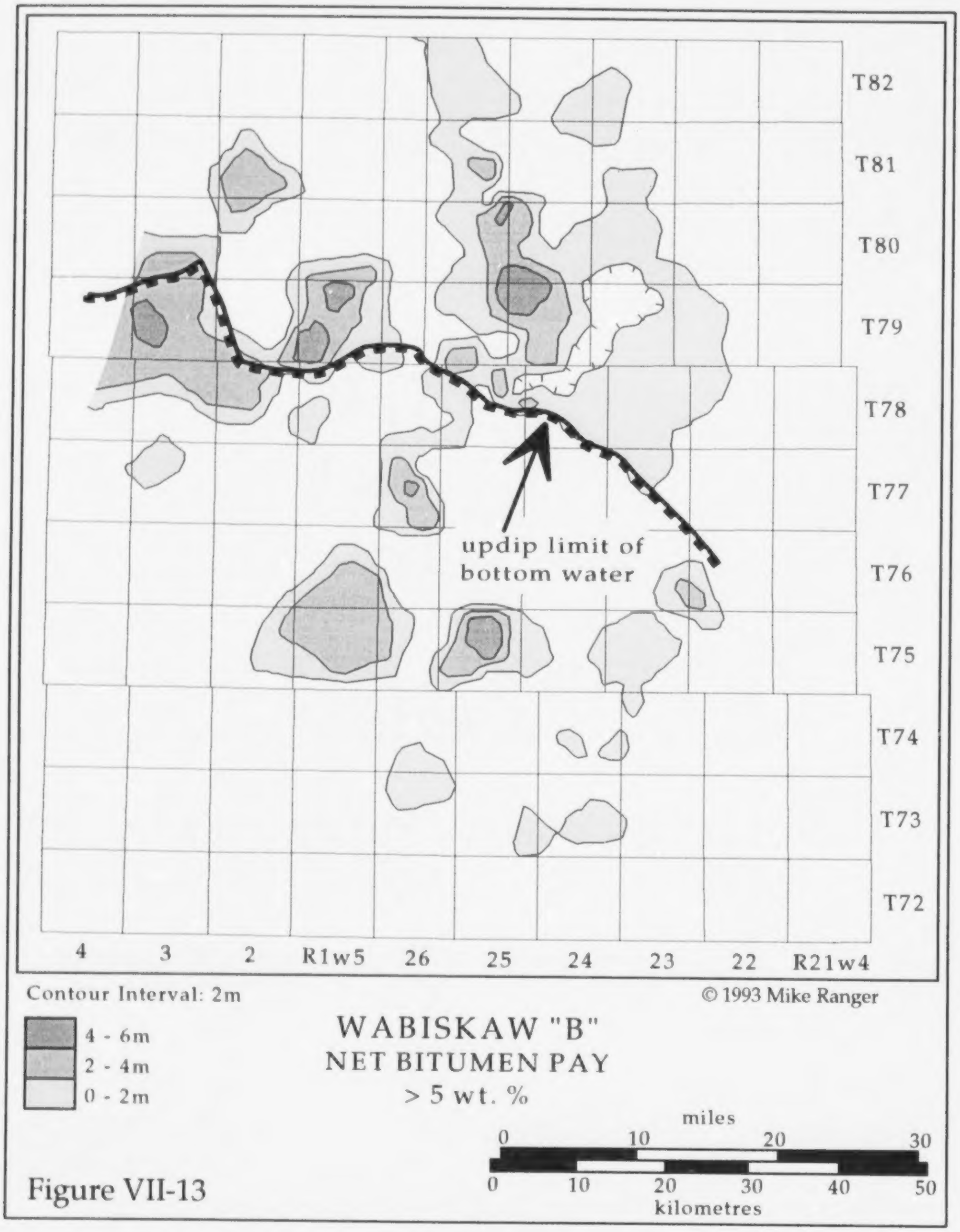
WABISKAW "A"
NET BITUMEN PAY
> 5 wt. %

Figure VII-12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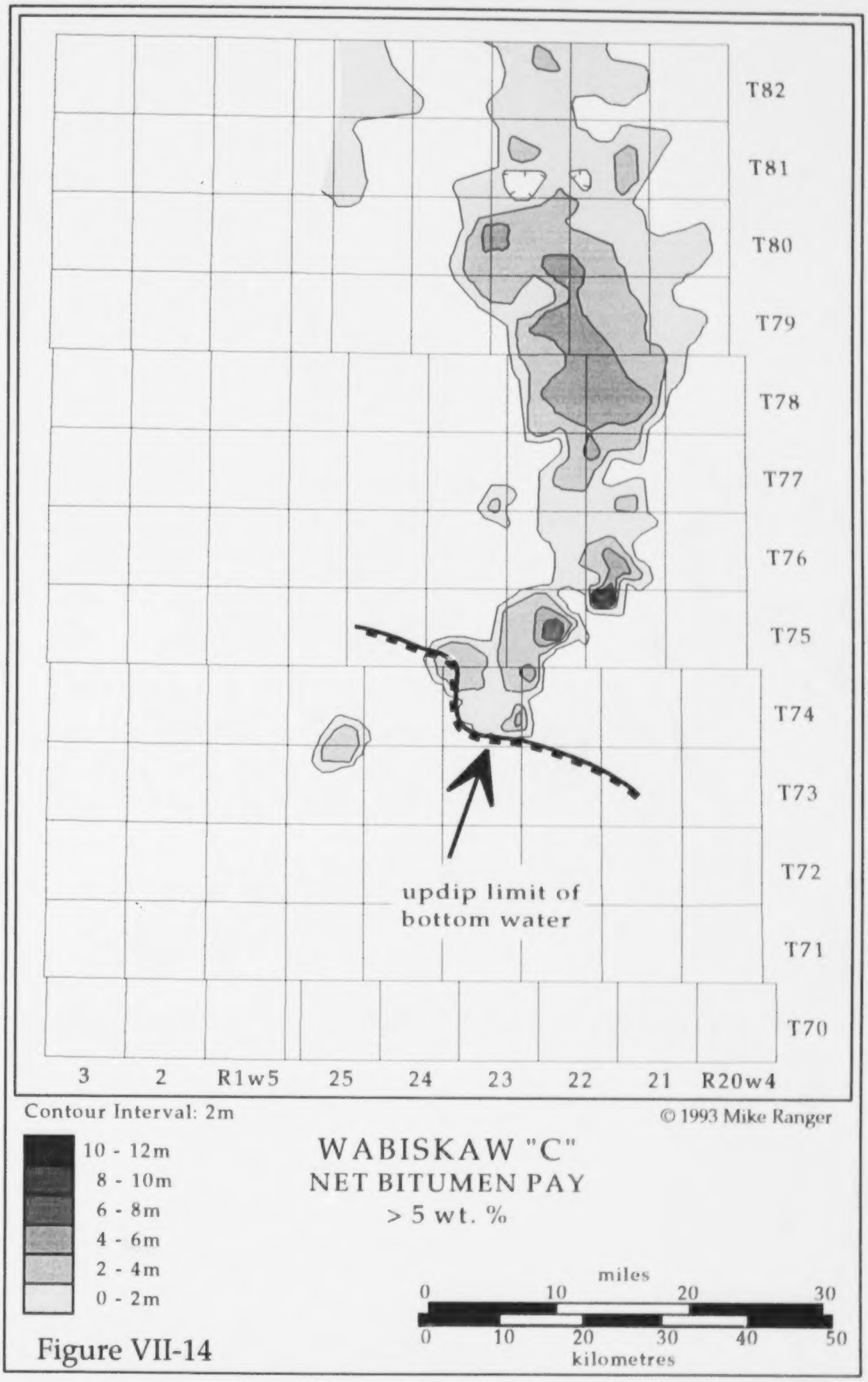
4
3
2
R1w5
26
25
24
23
22
R21w4
updip limit of bottom water
Contour Interval: 2m
4 - 6m
2 - 4m
0 - 2m
© 1993 Mike Ranger
miles
0
10
20
30
0
10
20
30
40
50
kilometres

WABISKAW "B"
NET BITUMEN PAY
> 5 wt. %

Figure VII-13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25
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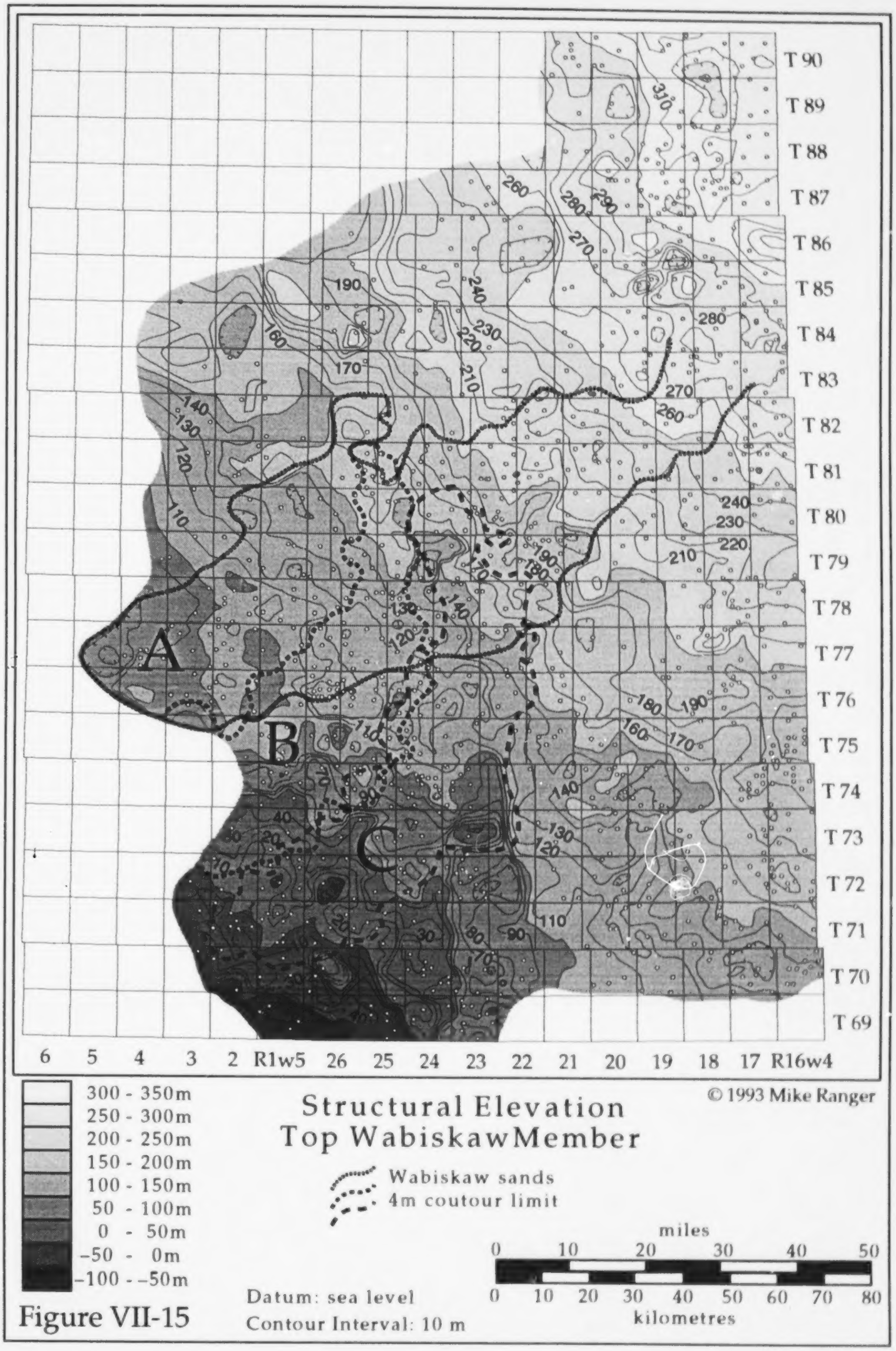
23
22
21
R20w4
updip limit of bottom water
Contour Interval: 2m
© 1993 Mike Ranger
10 - 12m
8 - 10m
6 - 8m
4 - 6m
2 - 4m
0 - 2m
WABISKAW "C"
NET BITUMEN PAY
> 5 wt. %
miles
0
10
20
30
0
10
20
30
40
50
kilometres

Figure VII-14

approximately 1.7 m per km or 0.1° (Fig. VII-15). The bitumen-water contacts are not horizontal, but dip in the same southwest direction and at only slightly less of an angle than the regional dip. Presumably this reflects a pre-deformational oil-water contact preserved due to the degradation and subsequent immobility of the bitumen (Ranger and Pemberton, 1992). The presence of an underlying water leg may be a detriment or may be desirable in an *in situ* recovery scheme depending on the engineering strategy and methods, and therefore the areal extent of the water leg is vital information when prospecting for a suitable area for a pilot site and ultimately for a commercial recovery scheme. Each of the three reservoirs also contains gas reserves (Fig. VII-16, VII-17 and VII-18), the largest being in the Marten Hills field (Benson and James, 1974), which is hosted mostly by the Wabiskaw "B" as well as underlying Mississippian carbonates. Other gas pools in the area include Hoole, Doucette and Pelican, as well as several smaller accumulations. Gas occurs in a number of horizons adjacent to the Wabiskaw Member sands, including the Wabamun, McMurray, Grand Rapids and Pelican (Viking) formations. Gas accumulations, even small localised ones are normally a severe detriment to *in situ* recovery schemes, acting as thief zones for the heating medium at the top of a reservoir. On the other hand, significant nearby gas reserves can be attractive as an energy source and as a hydrogen feedstock for bitumen upgrading.

The bitumen trapping mechanism of all three reservoirs is a combination of stratigraphic and structural components, although the structural dip was probably more subdued at the time of migration than it is now (Ranger and Pemberton, 1992). The structural dip towards the southwest forms the trap in that direction, and the sands gradually become shalier laterally and updip forming the stratigraphic trapping component in all other directions. The Wabiskaw "A" sand does not pinch out in the Wabasca study area, but continues in an updip direction over the Grosmont High to the northeast and into the McMurray subbasin. Over the Grosmont High this sand is thin and shaly, and is probably only marginally economic, but it recovers in the McMurray subbasin.

The gas is trapped in small structural highs, and no stratigraphic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210
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130
140
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A
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C
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110
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80
90
70
300 - 350m
250 - 300m
200 - 250m
150 - 200m
100 - 150m
50 - 100m
0 - 50m
-50 - 0m
-100 - -50m
Wabiskaw sands
4m coutour limit
miles
0
10
20
30
40
50
0
10
20
30
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80
kilometres

Structural Elevation
Top Wabiskaw Member

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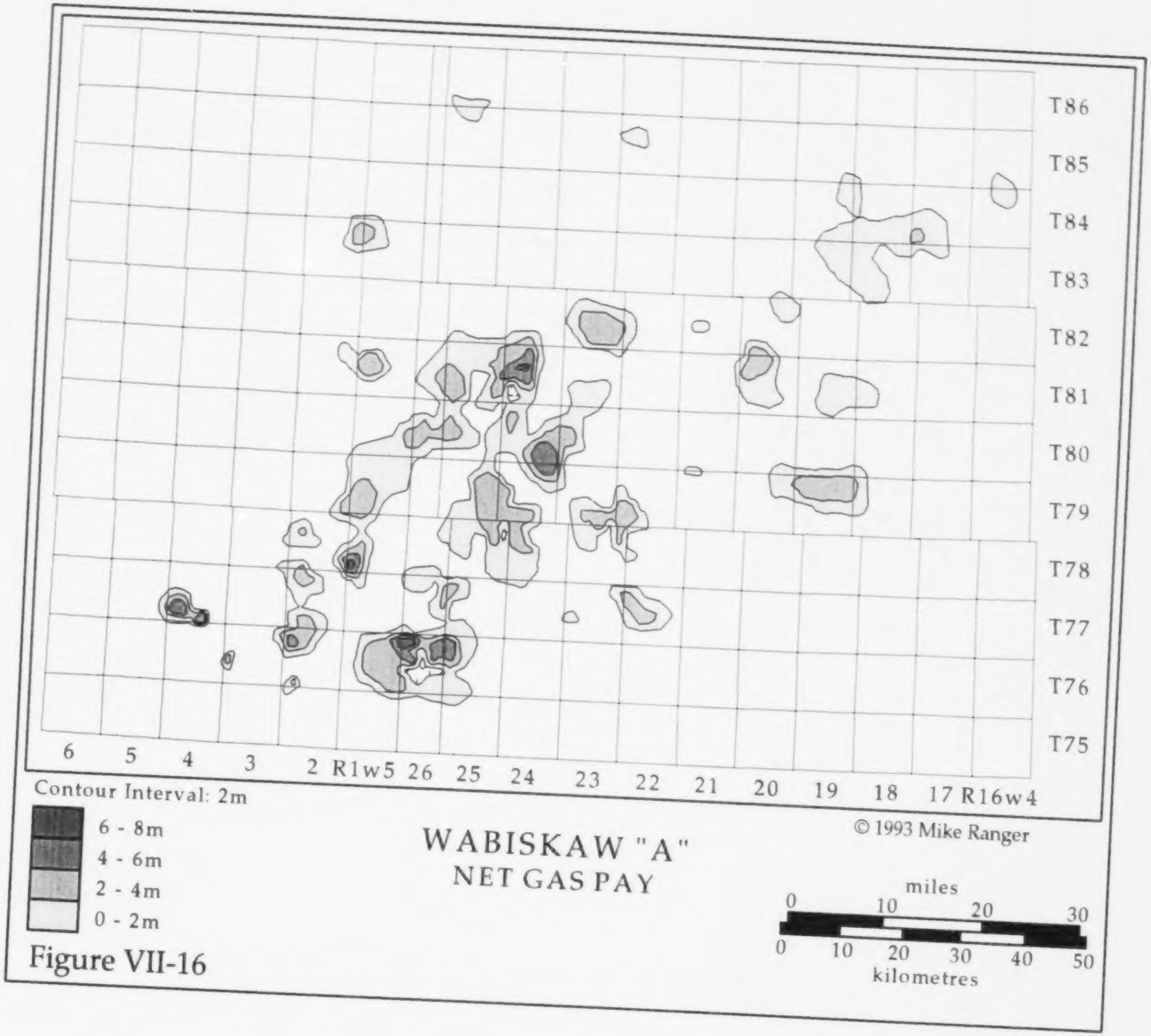
Datum: sea level
Contour Interval: 10 m

Figure VII-15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Contour Interval: 2m
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WABISKAW "A"
NET GAS PAY
© 1993 Mike Ranger
miles
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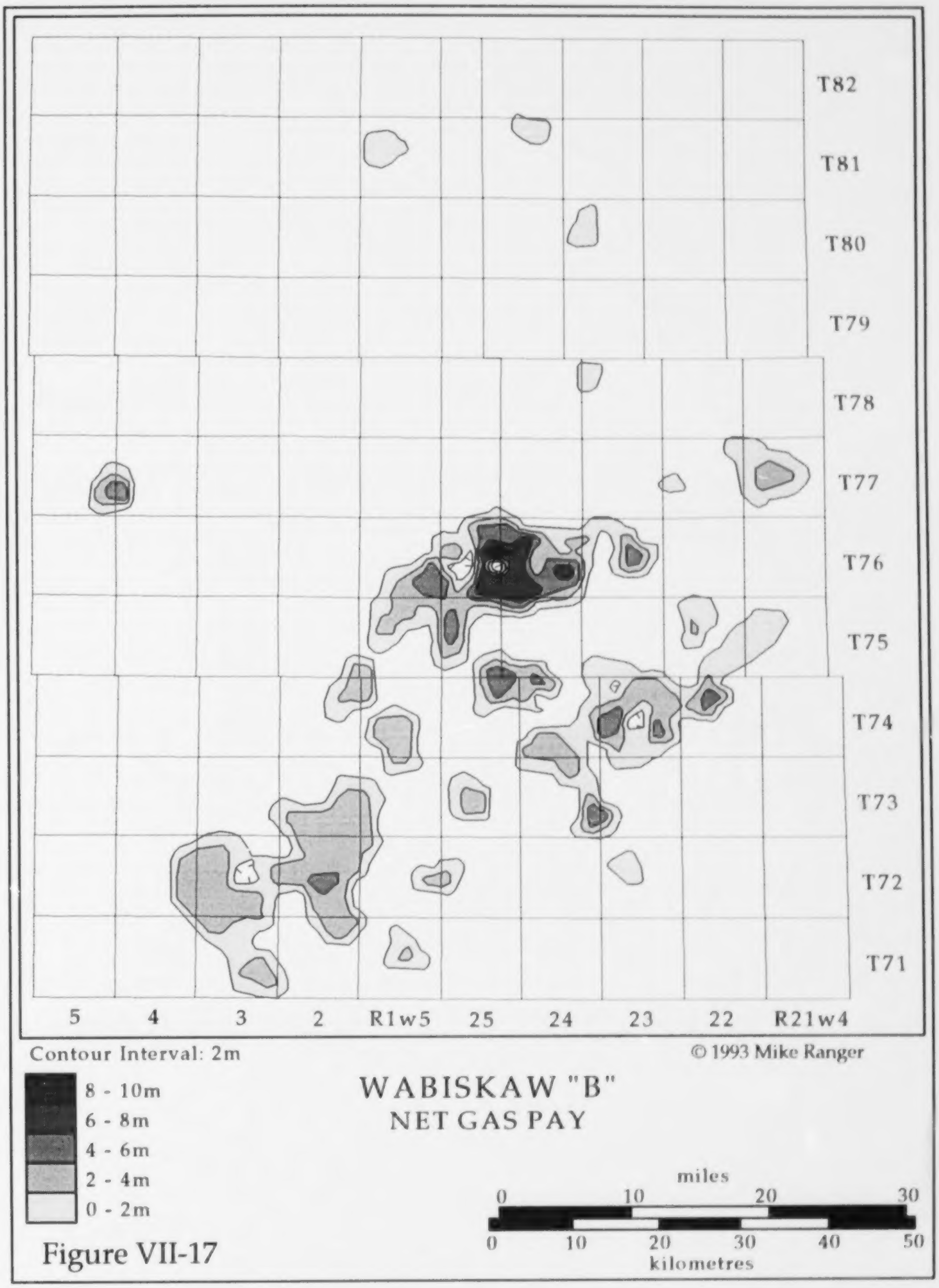
kilometres

Figure VII-16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Contour Interval: 2m
© 1993 Mike Ranger
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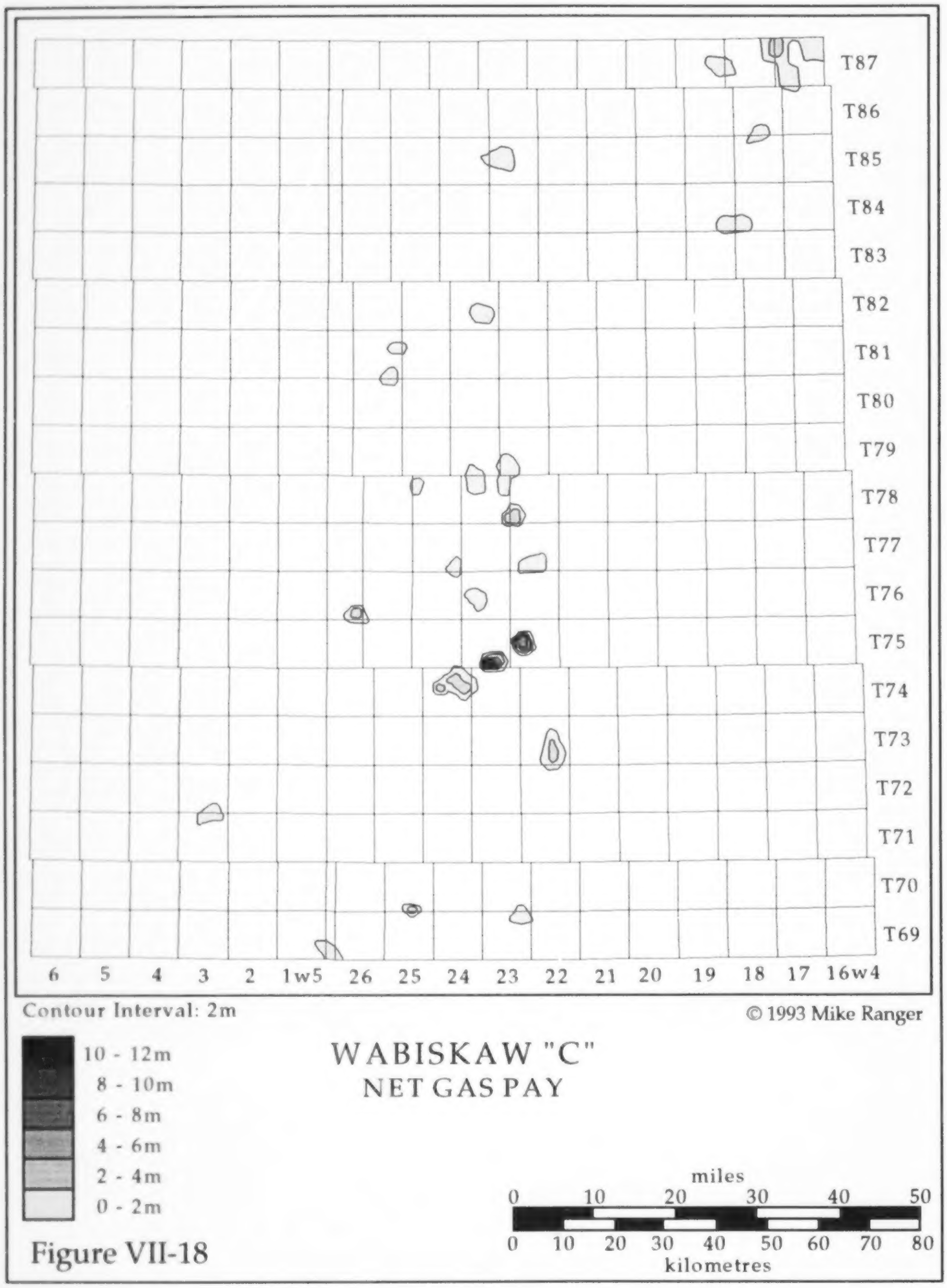
Figure VII-17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19
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17
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Contour Interval: 2m
10 - 12m
8 - 10m
6 - 8m
4 - 6m
2 - 4m
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miles
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30
40
50
0
10
20
30
40
50
60
70
80
kilometres

WABISKAW "C"
NET GAS PAY

© 1993 Mike Ranger

Figure VII-18

component is evident. Many of these structural highs, especially the larger gas traps such as Marten Hills are due to highs on the sub-Cretaceous unconformity and concomitant draping of overlying Cretaceous sediments.

Based on well log analysis, porosities vary between 25 and 28% in the sandier facies that make up the most prospective reservoirs. In these facies, log derived oil saturation values vary considerably between 0.6 and 0.8. These correspond to bitumen values of 7.5 to 10 wt% reported from publicly available core analyses. The other significant parameter that can influence the performance of a recovery scheme is viscosity. *In situ* viscosity values are difficult to obtain, however, because of the problem of obtaining a representative sample. Some samples from the Wabiskaw bitumen have been analysed, but give results varying widely from 500 to 42,000 centipoise (cP) (R. Sharpe, pers. comm.). Nonetheless, viscosity values in this range are significantly lower than viscosities from other parts of the Athabasca Deposit, where values of over 1,000,000 cP are not at all uncommon. These viscosity parameters make the Wabiskaw bitumen comparable to Lloydminster type heavy oils rather than other oil sands, and in some areas of the deposit primary recovery of the lighter bitumen is possible. These circumstances have in fact prompted attempts at primary recovery using horizontal drilling techniques in township 81, range 22W4.

CONCLUSIONS

1. The Wabiskaw Member reservoir in the Wabasca area can be subdivided into three sand units, and each is independently mappable. They overlap one another and appear to onlap onto a large Paleozoic headland subcropping in the northwest.

2. Each of the sands is interpreted as a lowstand shoreface forming the shoreline surrounding the Paleozoic highland, which remained exposed during early Clearwater transgressions. The facies successions, the coarsening upwards and sandier upwards nature of the units, and the trace fossil suites all support the interpretation as shoreface sand bodies. The lack of beach/foreshore or any indication of exposure suggests that each

transgressive phase was accompanied by minor erosion, or that, especially in the northeast, only lower to middle shoreface environments ever existed, and flooding is represented only by a change to deeper water facies.

3. With the recognition and discrimination of the three separate sands in the subsurface, the pattern of the bitumen reserves is resolved, and their predictability is enhanced. When each sand unit is evaluated separately for its bitumen content, the trapping mechanism appears to be stratigraphic due to the updip pinchout of each of the sands. The "A" sand does not totally pinch out in the study area, but extends over the Grosmont High and into the McMurray subbasin. Each of the three sand reservoirs has a separate downdip water leg.

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CHAPTER VIII

NEW EVIDENCE FOR THE TIMING AND MECHANISM OF OIL MIGRATION AND TRAPPING IN THE ATHABASCA OIL SAND DEPOSIT

INTRODUCTION

Considering that the Athabasca Oil Sands Deposit (Fig. VIII-1) constitutes what is probably the largest single hydrocarbon accumulation on earth, there is surprisingly little agreement on its migration and trapping mechanisms, and the timing of these events. In the course of a resource inventory of the south Athabasca area, regional mapping of the bitumen-water contact at the base of the Athabasca Deposit has led to new evidence relevant to all three of these topics.

The aspect that has received the most attention in recent years is the source of the hydrocarbons (du Rouchet, 1985; Moshier and Waples, 1985; Brooks *et al.*, 1988; Brooks *et al.*, 1989; Creaney and Allan, 1990; Allan and Creaney, 1991; Creaney and Allan, 1992). Recent studies of biomarkers appear to pin down the source beds as dominantly Jurassic in age, with possibly some contribution from source rocks of Triassic and Mississippian age (Allan and Creaney, 1991; Creaney and Allan, 1992). This implies, of course, that long distance migration has occurred from a source in the west to a trap in the east. This theory for the origin for the oil sands is not unanimously accepted, and in fact, has at times been one of the least acceptable source theories (Corbett, 1955a, 1955b). Various other theories include in-situ formation of bitumen (Ball, 1935; Hume, 1951; Corbett, 1955a, 1955b), leaking from underlying Paleozoic reef reservoirs (Sproule, 1938, 1955) and mechanical deposition of the tars eroded from underlying Devonian bitumen (Link, 1951a).

HISTORY OF THOUGHT

In Situ Source Theory

At one time it was suggested that the bitumen is an immature oil that

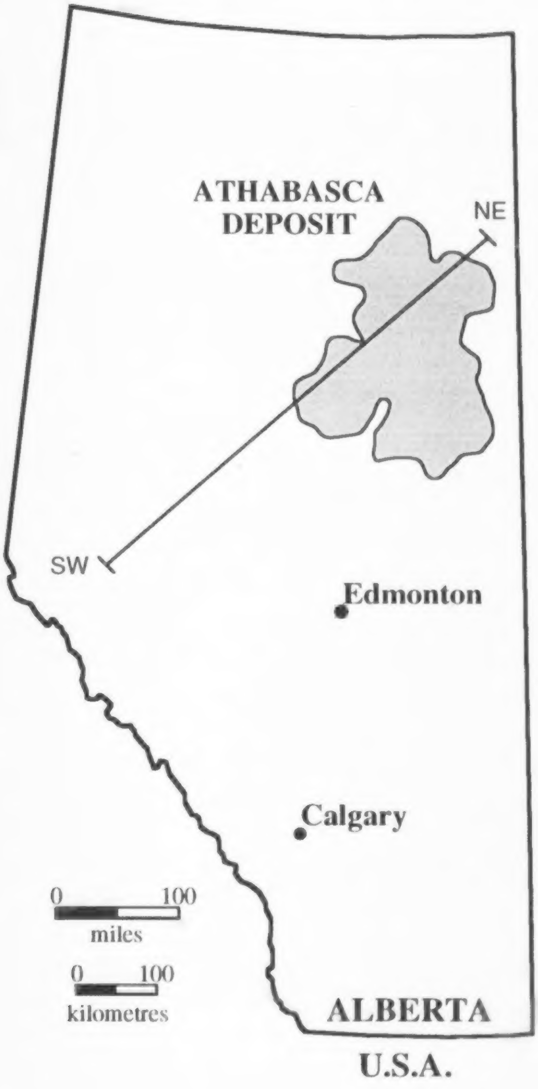
ATHABASCA
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Figure VIII-1. Location map, Athabasca Oil Sands Deposit. NE-SW line is the cross-section location for figures VIII–14 and VIII-15.

was sourced from organic matter contained in the enclosing reservoir rocks (Ball, 1935; Hume, 1951; Corbett, 1955a, 1955b). A possible alternative chemical source was thought to be humic acids in rivers that existed contemporaneously with deposition of the reservoir rocks (Corbett, 1955a, 1955b). This theory is all but discounted today based on modern knowledge of petroleum geochemistry and organic maturation. The Athabasca bitumens are not immature oils, but degraded conventional oils (Deroo *et al.*, 1977), and the reservoir rocks and surrounding possible source shales have not experienced conditions necessary for formation of oil (HacqueBard, 1977). It is certainly possible however, that some of the associated gas is biogenic in origin, obviating the need for deeply buried source.

Leaky Reef Theory

With the discovery in the late 1940's of major petroleum reservoirs in Paleozoic reefs underlying and down dip from the Athabasca Deposit, it was suggested that the Athabasca bitumens are the result of oil breaching these reef reservoirs and accumulating in the overlying Lower Cretaceous sands (Sproule, 1938, 1955). The problem with this theory is that mass volumes are totally inadequate. However it is possible that reefs near the sub-Cretaceous unconformity constitute part of the migration path (du Rouchet, 1985). There is commonly no seal between porous carbonates that subcrop at the unconformity and overlying sand reservoirs, and many of these porous carbonates are themselves bitumen reservoirs.

Eroded Devonian Tar Theory

Bitumen deposits hosted by Devonian carbonates subcrop at the sub-Cretaceous unconformity. Some researchers have suggested that these deposits were eroded during Lower Cretaceous exposure, and subsequently deposited along with regular sediments (Link, 1951a, 1951b, 1954). This theory is untenable because the bitumen, although presently having a density equal to or slightly greater than water, displays a conventional reservoir relationship, that is, gas overlies bitumen which overlies water. The few rare exceptions to this relationship can easily be explained by the fact that the bitumen is presently immobile at reservoir conditions, and an overlying "paleo-gas cap" has breached its seal and been displaced by water. Furthermore, maturation studies have suggested that by far the dominant period of oil formation in the western Canada basin is during major subsidence in the Upper Cretaceous (Deroo *et al.*, 1977), long after exposure of the Devonian reservoirs at the unconformity. The bitumen therefore must have accumulated as a conventional oil with density less than water, not as blebs of eroded tar.

Long Distance Migration Theory

It is generally accepted today that the bitumen in the Athabasca Deposit originated from source beds downdip in the western foreland Basin as these beds subsided through oil window conditions (Deroo *et al.*, 1977; Creaney and Allan, 1990; Creaney and Allan, 1992). They then underwent long distance migration to the east, there to be trapped as conventional oils. These conventional oils were then degraded to higher density, high viscosity bitumen through water-washing and or bacterial activity (Deroo *et al.*, 1977; Brooks *et al.*, 1988) Thus, despite its size, no extraordinary mechanism or chemistry need be invoked to account for the accumulation. This theory is not a modern development however. Gussow (1955) came to essentially the same conclusions early in the debate on bitumen origin. Much of the modern evidence for the source of the bitumen confirms his earlier conclusions.

This short, historical review of the source theories does not do justice to the reasoning, discussion and evidence presented at the time of espousal of the various theories. For detailed reviews of the history of ideas on the origin of the Athabasca Deposit see Coneybear (1966), Vigrass (1968) and DeMaison (1977).

Western Source Beds

Based purely on structural relationships Gussow (1955) came to the conclusion that the source beds of the oil sands were primarily Jurassic in age, with possible contributions from shales of Triassic, Permo-Pennsylvanian and Mississippian age. A primarily Triassic source, with some possible contribution from Jurassic shales, has been suggested for the

Peace River Oil Sands Deposit and, by extension, for all of the Cretaceous oil sands deposits (du Rouchet, 1985). The Lower Cretaceous shales have been suggested as possible source beds for the oil sands (Deroo *et al.*, 1973; Deroo *et al.*, 1977; Hacquebard, 1977), given that they are the same age as the reservoir rocks and are thus stratigraphically directly downdip from the reservoir. Allan and Creaney (1991) have determined that the Lower Cretaceous Joli Fou Shale is a regional seal isolating reservoir systems above and below it from each other. Therefore the only possible Lower Cretaceous source beds must be confined to the Mannville Group directly underlying the Joli Fou shale. However Moshier and Waples (1985) showed that even using very optimistic assumptions, the Mannville Group could not have generated the volume of hydrocarbons known to exist in the oil sands deposits of Alberta.

The geochemical classification of oils by Deroo *et al.* (1977), and recent work by Allan and Creaney (1991), who used biomarkers to fingerprint oils and source beds throughout the Western Canada basin, have divided the oils of the basin into distinct families. Correlation of these geochemical families to source rock geochemistry, and recognition of discrete reservoir systems constitute persuasive evidence that the source of the Lower Cretaceous oil sands and heavy oils is primarily the Jurassic Nordegg Member, and the Mississippian Exshaw shale.

Migration Mechanism

The driving mechanism of fluid migration for the precursor oils of the oil sands has been a controversial issue. There are two competing theories for the migration mechanism: compaction and expelling of water and oil either as separate phase or in miscible solution (Gussow, 1955; Vigrass, 1968; DeMaison, 1977) and topographically driven hydrodynamic flow (DeMaison, 1977; Hitchon, 1984; Garven, 1989). The hydrodynamic model depends on the establishment of thrusting and basin uplift (Laramide orogeny) in the west, which established the Rocky Mountains and formed a hydraulic head for the major recharge area in the foreland basin.

Timing

The timing of hydrocarbon generation and migration in the Athabasca Deposit must be discussed in relation to the timing of the Late Cretaceous-Early Tertiary Laramide orogeny, because it is the initiation of the Laramide that produced the deep burial of potential source beds and initiated compaction water flow. Its culmination in the Paleocene caused the uplift in the west to produce the topography that would have made possible basin wide hydrodynamic flow. It is probable that little hydrocarbon generation took place much before Laramide, because potential source beds would not have been buried deeply enough to be exposed to temperatures that would initiate organic diagenesis (Deroo *et al.*, 1977).

Gussow (1955) deduced that migration and trapping in the Lloydminster heavy oil fields, and by extension the oil sands deposits, took place no later than Lea Park (Campanian) time based on an analysis of solution gas saturation pressures. Secondary migration would have been driven by compaction dewatering and buoyancy effects, because little or no Laramide uplift existed at this time to provide a hydraulic head to drive a hydrodynamic basin system.

The hydrodynamic migration model of Garven (1989) would require secondary migration and trapping to have commenced no earlier than Paleocene when Laramide uplift provided the topography to drive a basin wide hydrodynamic system. Once established, however, hydrodynamic drive for petroleum migration could have continued through late Tertiary until Pliocene time when the regional flow system was disrupted by erosion.

Trapping Mechanism

The trapping mechanism for the bitumen in the Athabasca Deposit has also been a controversial topic for many years. The vast size of the deposit did not allow the recognition of a trapping mechanism until many wells had been drilled into the deposit providing a structural data base. In fact Corbett (1955b) used the apparent lack of recognition of a trap as evidence for the in-situ theory of bitumen accumulation as immature oil. Gussow (1955) refused to accept the theory, preferring long distance migration and therefore suggested the existence of a stratigraphic trap. Vigrass (1968) recognised the existence of an updip roll-over and reversal of dip from the regional southwest dipping homoclinal structure of the top of the reservoir. This roll-over is now a well known feature of the structural setting and is attributed to dissolution of underlying salt from the Middle Devonian Prairie Evaporite. Its existence and proximity to the eastern limit of the bitumen suggests that anticlinal structural closure provided at least part of the trapping mechanism.

The problem with invoking a purely structural trapping mechanism is that bitumen is known to be trapped down dip on the southwestern flank of the anticline at least 500 metres below the level of a distinct bitumen/water contact that exists on the opposite flank of the anticline. It is this that has led to the common belief that structural trapping is not sufficient and that there must be a significant stratigraphic component to the mechanism (DeMaison, 1977). As an alternative, Mossop (1980) suggested that oil initially migrating updip would have undergone biodegradation very early in its migration history, forming a bitumen plug that prevented further fluid displacement, and creating an up-dip seal to the trap. Masters (1984) suggested that the trap was entirely structural, and that the anomalies in the distribution of the bitumen are due to structural deformation of the trap after the oil was degraded and "frozen" in place.

THE NATURE OF THE BITUMEN-WATER CONTACT

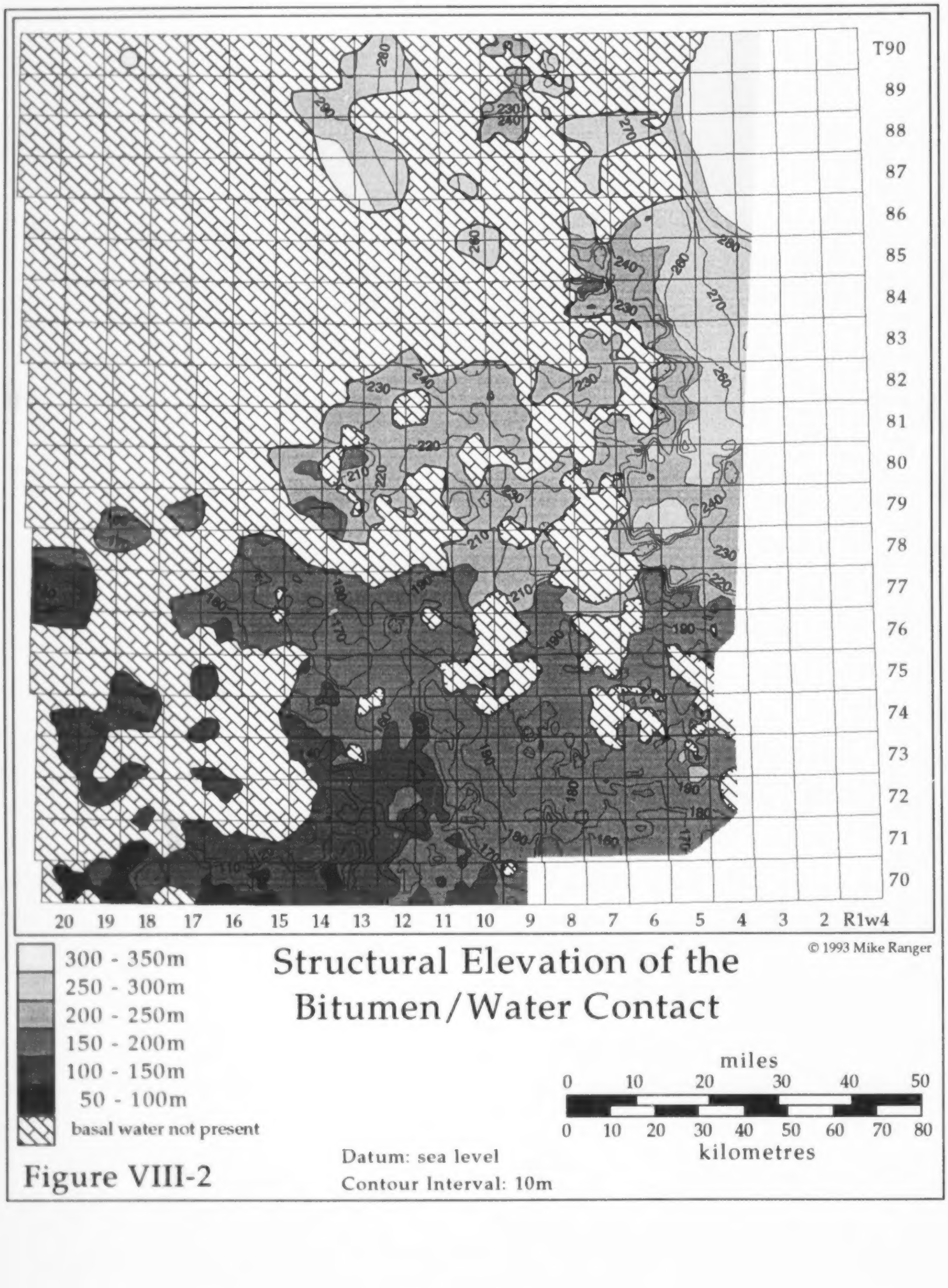
Routine regional mapping of the bitumen-water contact at the base of the Athabasca Deposit has led to new evidence relevant to all three topics discussed above, that is the migration, timing and trapping of the bitumen deposits in the Athabasca Deposit. There exists a discrete bitumen-water contact under much of the eastern and southwestern portion of the Athabasca Deposit. This contact appears to be a single continuous horizon with only a few rare exceptions where some wells appear to indicate local multiple stacked reservoirs with two or more bitumen-water contacts. The bitumen-water contact is easily recognised on geophysical logs, especially on the deep resistivity response where it is indicated by either a sharp or gradual drop in resistivity over a porous reservoir sand. The SP log is also useful, indicating the contact by an increase in potential over water saturated porous sands. In wells where the contact horizon intersects a shale facies, the exact depth of the contact cannot easily be determined, but its existence is evident by bitumen saturated sands above the shale and water saturated sands below.

The structural elevation of the bitumen-water contact is not horizontal on a regional scale (Fig. VIII-2). A first order observation of its attitude indicates a distinct southwesterly dip in southwest Athabasca, rising gradually to the north to arch over the Ft.McMurray Area (Township 90). The contact intersects the unconformity over much of the northwest and west-central part of the basin, which is shown on the map as a brickwork pattern. Over these areas there is no basal water zone in the Mannville reservoirs. However it is possible that the water leg may continue through subcropping porous Devonian carbonates. No attempt has been made in this study to document this. Note also that the contact horizon is not perfectly planar, but has many perturbations over its surface (Fig. VIII-2).

An assumption is made here that is critical to the arguments developed from the observations of the bitumen-water contact. That is that the oil was originally trapped in a conventional density relationship with gas and water *i.e.* gas overlying oil overlying water, and that the fluid contacts were originally horizontal. These contacts are now frozen in place because of the biodegradation of the oil and high viscosity of the bitumen end product.

In almost all instances where gas and or water is present with the bitumen this conventional density relationship is observed even though much of the bitumen is presently denser than water, and therefore the precursor oil originally had a lower density and lower viscosity.

In some instances a water leg is seen to directly overly the bitumen. The existence of these overlying water zones have occasionally been used as evidence of bitumen with a density greater than water migrating into lows in the reservoir (Kidd, 1951). However, it is not uncommon to find a water leg below the bitumen as well as above, with no seal separating any of the fluids (Fig. VIII-3). Thus the bitumen is truly immobile in its current state at reservoir conditions, and it became immobile before its density was reduced below that of the underlying formation water. Therefore these overlying water zones cannot be examples of density settling of the bitumen. There can be little doubt that these zones represent "paleo-gas caps" that were breached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270
260
250
220
210
190
180
170
110
300 - 350m
250 - 300m
200 - 250m
150 - 200m
100 - 150m
50 - 100m
▨ basal water not present
miles
0 10 20 30 40 50
0 10 20 30 40 50 60 70 80
kilometres

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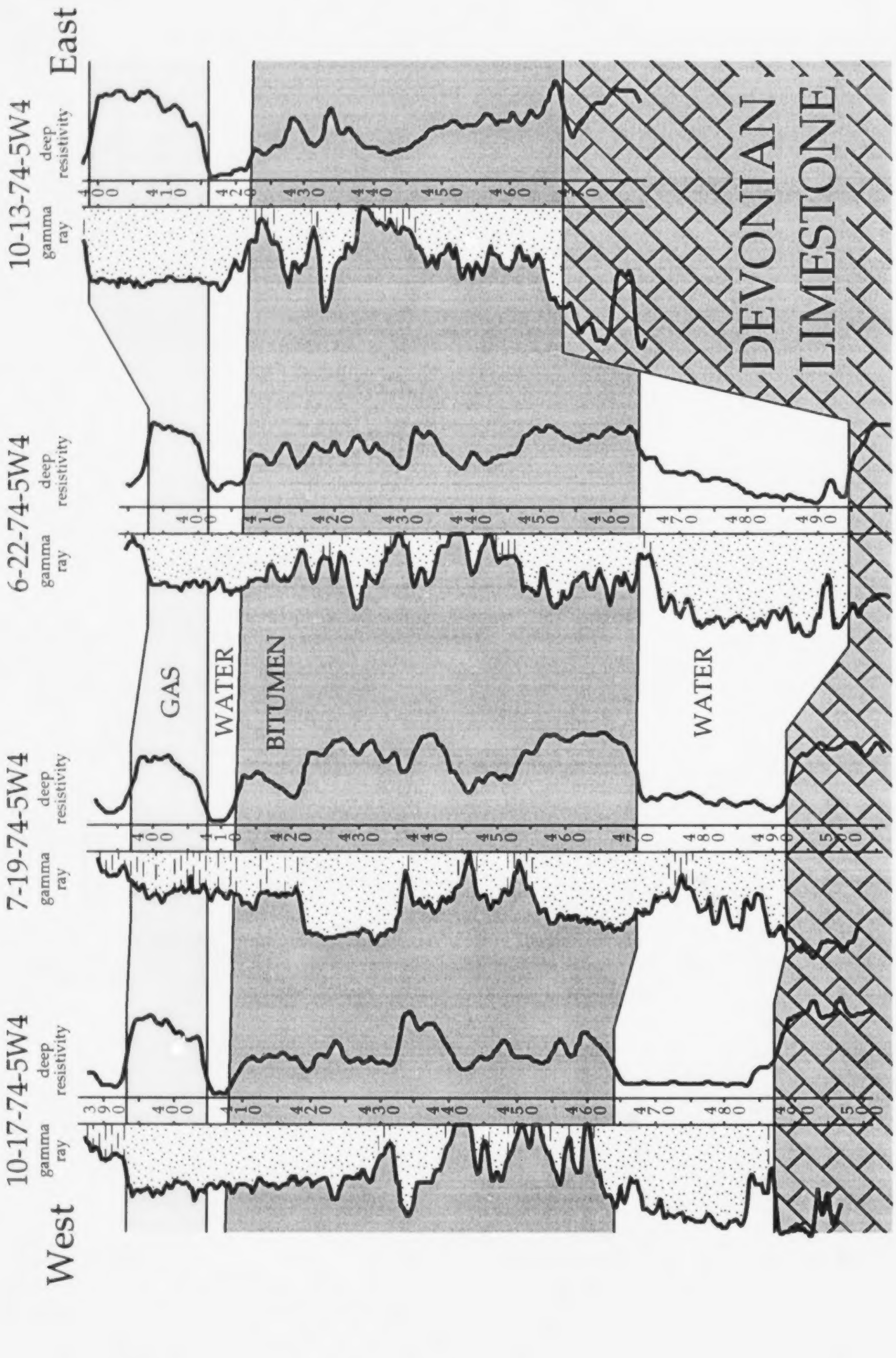
Structural Elevation of the Bitumen/Water Contact

Figure VIII-2

Datum: sea level
Contour Interval: 10m

Figure VIII-3. East-west cross-section through the Athabasca Oil Sands Deposit in township 74, range 5W4. This reservoir shows a normal oil field density relationship of water, oil and gas, except for an additional water leg between the oil (bitumen) and the gas. Note the presence of porous sand both above and below the bitumen, yet the bitumen has not migrated either upward or downward to displace the water. The water leg above the bitumen was presumably once part of the gas cap, but some of the gas has leaked off, and been displaced by water because the bitumen is immobile. Immobility of the bitumen is a result of two factors: it has a very high viscosity, and the density of the bitumen is very close to that of the formation water.


West
East
10-17-74-5W4
7-19-74-5W4
6-22-74-5W4
10-13-74-5W4
gamma ray
deep resistivity
GAS
WATER
BITUMEN
WATER
DEVONIAN LIMESTONE
390
400
410
420
430
440
450
460
470
480
490
500

or depressurised after the oil became immobile, allowing water to displace the gas. In some cases a remnant gas cap remains above the water (Fig. VIII-3).

The conclusion may be made that the immobilised fluid contacts are in fact paleo-horizons that were parallel to paleo-sea level at the time of degradation. The only other explanation is that the tilted fluid contacts preserve a hydrodynamic tilt. However the only possible source beds are deeper in the basin towards the southwest, and therefore large scale fluid migration must have occurred towards the northeast. But such a hydrodynamic system would have produced fluid contacts dipping towards the northeast, opposite to the southwestern dip observed today. Therefore any present day deviation from the horizontal represents structural deformation that has affected the reservoir since the time of oil degradation and subsequent immobility. There is an important implication to this deduction: by correcting the structure of the top of the reservoir so that the bitumen-water contact is flattened, the geometry of the trap during accumulation and degradation can be reconstructed.

MAPPING TECHNIQUES

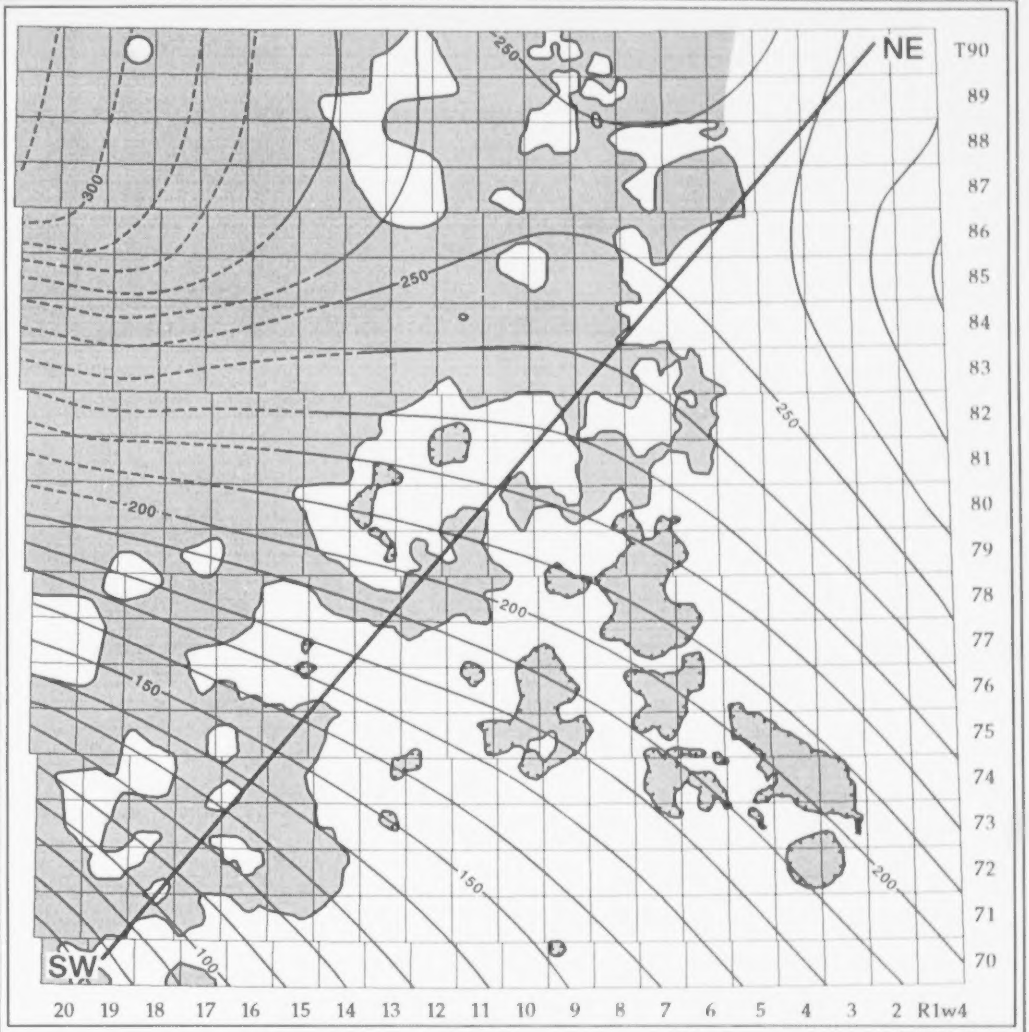
The high frequency perturbations on the structure elevation map of the bitumen-water contact (Fig. VIII-2) are due to a number of different causes. Because the contact horizon is immobilised in relation to the enclosing reservoir rocks, any structural dislocation affecting the reservoir will also affect the contact as long as the dislocation occurred after biodegradation of the bitumen. The most common structural anomalies are probably minor faulting and isolated collapse due to underlying salt dissolution or karst structure in the underlying Devonian carbonates. Also, the bitumen-water contact is not always sharp on the geophysical logs. In places it may be transitional over several metres, or there may be a stained zone at the base of the bitumen, masking the exact contact. Transitional or stained zones may result from the loss of volume due to biodegradation or water-washing of the precursor oils. Anomalous contact elevations may also simply be error, either in the surveyed ground elevations, or the logging operation.

Trend analysis was run on the bitumen-water contact to eliminate all of this high frequency "noise" and to extract the low order regional trends. One advantage of the trend surface analysis is that where the bitumen-water contact is truncated by Devonian highs on the sub-Cretaceous unconformity, it is possible to extrapolate the trend of the contact through these zones. A simple third order trend was used to estimate the surface (Fig. VIII-4). (Trend surface analysis is a special case of multiple regression wherein a plane is fitted by least squares to a set of data points in 3 dimensional space. A third order trend fits a curved plane that is constrained to no more than 2 inflections). This trend can then serve as a datum from which the regional structure on the top of the reservoir can be corrected.

The regional structure of the reservoir can be estimated by mapping the top of the Wabiskaw Member (Fig. VIII-5), which is the uppermost of the reservoir units. The top of this unit is a marked by a persistent and readily recognised stratigraphic horizon that has a distinct signature on resistivity logs. This horizon is a widespread shale, which probably constitutes part of the seal for the the Athabasca reservoirs, and thus represents the configuration of the top of the trap. A trend analysis was also run on this surface to filter out high frequency noise.

Given these topological data, an actual reconstruction of the reservoir surface can be approximated by simply subtracting the actual elevation of the bitumen-water contact from the elevation of the Wabiskaw marker. In effect this treats the bitumen-water contact as a datum and thus corrects the reservoir structure so that the datum is flattened. This provides the detailed representation of the original configuration of the trap. Furthermore some of the possible errors, such as ground elevation survey errors and any post-degradation faulting and collapse are cancelled out by the subtraction of surfaces. One drawback with this method is that over much of the western part of the Athabasca Deposit, the bitumen-water contact does not exist since it is truncated by highs on the sub-Cretaceous unconformity. Over these areas the extrapolated trend of the bitumen-water contact can be substituted for the actual horizon.

A smooth geometric representation of the original attitude of the trap can also be produced by subtracting the trend of the bitumen-water contact from the trend of the Wabiskaw marker.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71
70
20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 R1w4
300
250
250
250
200
200
200
150
150
100

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Structural Elevation of the Bitumen/Water Contact

3rd Order Trend Surface

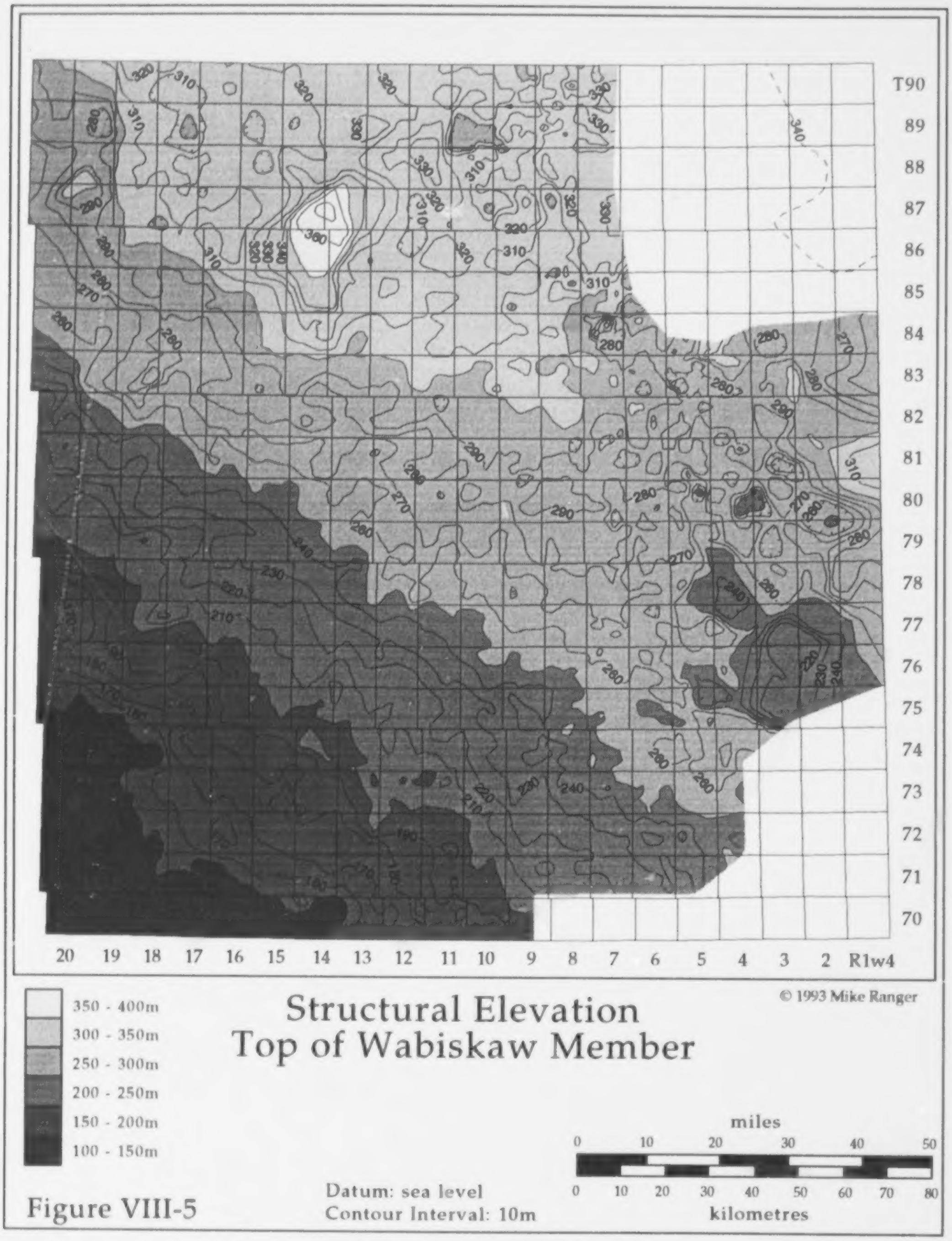
▨ Area of extrapolated trend

NE - SW line: Figure VIII-8 cross-section location

miles
0 10 20 30 40 50
0 10 20 30 40 50 60 70 80
kilometres

Figure VIII-4

Datum: sea level
Contour Interval: 10m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360
340
330
320
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270
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190
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170
350 - 400m
300 - 350m
250 - 300m
200 - 250m
150 - 200m
100 - 150m
miles
0 10 20 30 40 50
0 10 20 30 40 50 60 70 80
kilometres

Structural Elevation
Top of Wabiskaw Member

© 1993 Mike Ranger

Datum: sea level
Contour Interval: 10m

Figure VIII-5

DISCUSSION

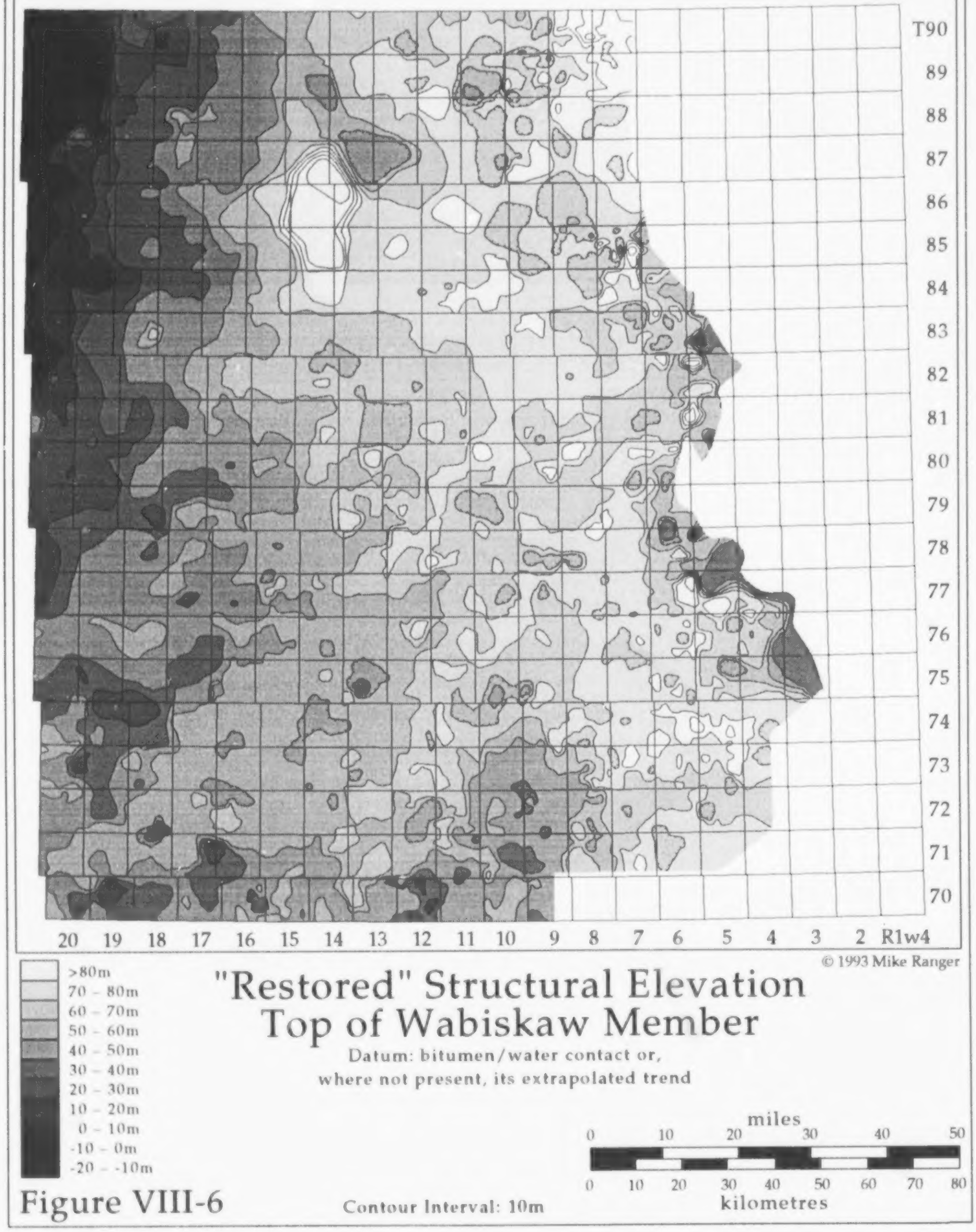
There are two major components to the structure of the top of the Wabiskaw, the primary being the homoclinal Laramide subsidence to the southwest into the foreland basin. No less significant from an economic point of view is the reversal in structural dip to the east (Fig. VIII-5). This is caused by dissolution of underlying Middle Devonian salt accompanied by structural collapse, and differential compaction of overlying strata.

Trap

The structure of the Wabiskaw marker corrected by flattening on the bitumen-water contact is shown in Figure VIII-6. This surface represents the trap structure restored to its configuration at the time the oil was degraded to bitumen and immobilised. The trend of this surface (Fig. VIII-7) emphasises the broad regional attitude of the original trap structure.

Since the general southwest dip of the bitumen-water contact is only slightly less than regional structural dip of the top of the Wabiskaw, the restored trap structure has a much gentler southwesterly dip and provides a tremendously larger closure area than exists today (Fig. VIII-8). The configuration of the trap is that of a very broad, very low amplitude anticline with axis along the northeastern edge of the basin, confirming the existence of what has been called the "Athabasca Anticline" (Masters, 1984). The maximum east-west closure across the width of the anticlinal trap extended for over 150 km, but maximum vertical closure was little more than 60 m (Fig. VIII-7).

The distribution of bitumen in the restored trap indicates that the anticlinal structure is by itself a sufficient trapping mechanism for the southern and central part of the deposit (Fig. VIII-6). No stratigraphic component or updip bitumen plug is required at least in the southeast (Fig. VIII-9). The northern edge of the anticline is eroded however, and its configuration will never be known. Although the restored anticlinal structure plunges towards the south southeast, the northern apex shows no reversal of plunge up to the erosional edge. It is generally accepted that the McMurray Formation prograded northward into the boreal sea, and it may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R1w4
>80m
70 - 80m
60 - 70m
50 - 60m
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30 - 40m
20 - 30m
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-10 - 0m
-20 - -10m
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30
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0
10
20
30
40
50
60
70
80
kilometres

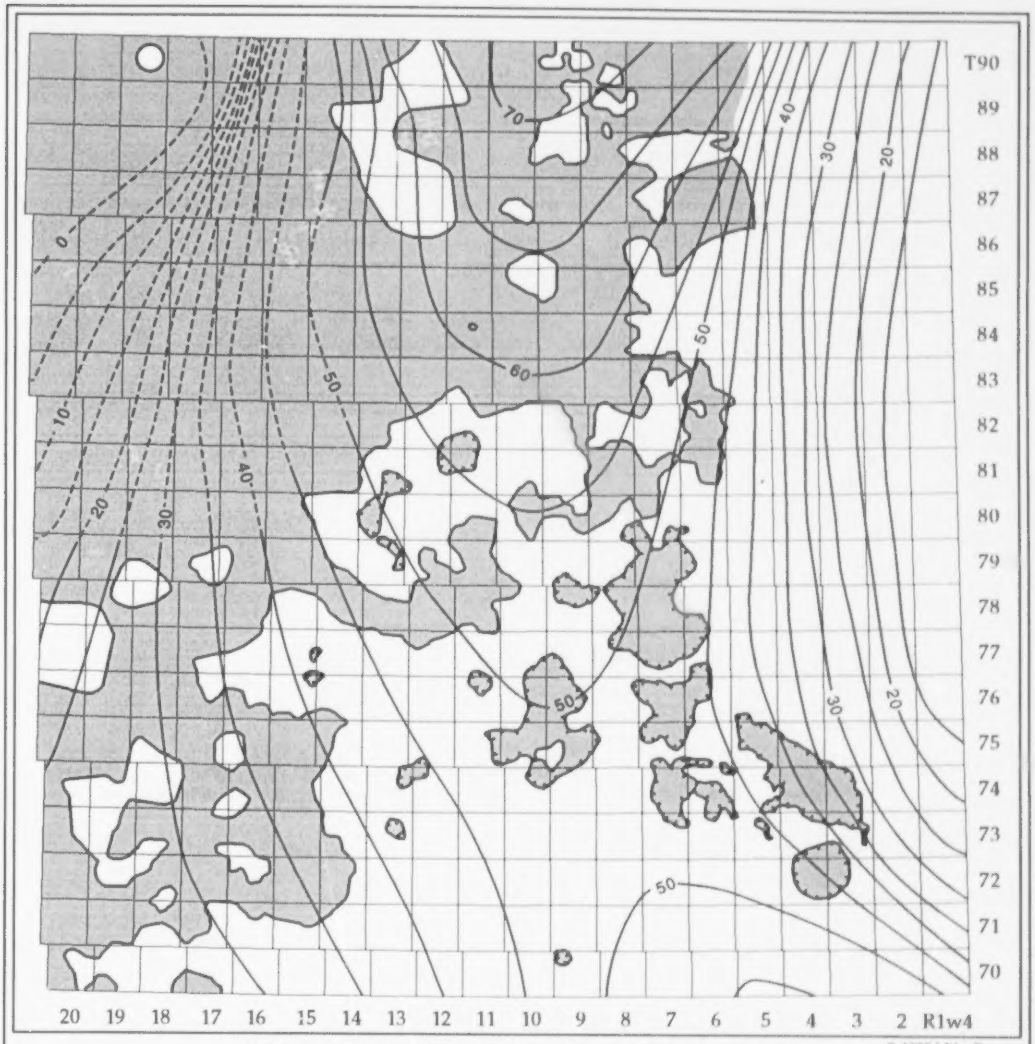
© 1993 Mike Ranger

"Restored" Structural Elevation
Top of Wabiskaw Member

Datum: bitumen/water contact or,
where not present, its extrapolated trend

Figure VIII-6

Contour Interval: 10m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30
40
50
30
20
50

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"Restored" Structural Elevation Top of Wabiskaw Member

3rd Order Trend Surface

Datum: 3rd order trend of
the bitumen/water contact

▨ Area of extrapolated trend of the bitumen/water contact

miles
0 10 20 30 40 50
0 10 20 30 40 50 60 70 80
kilometres

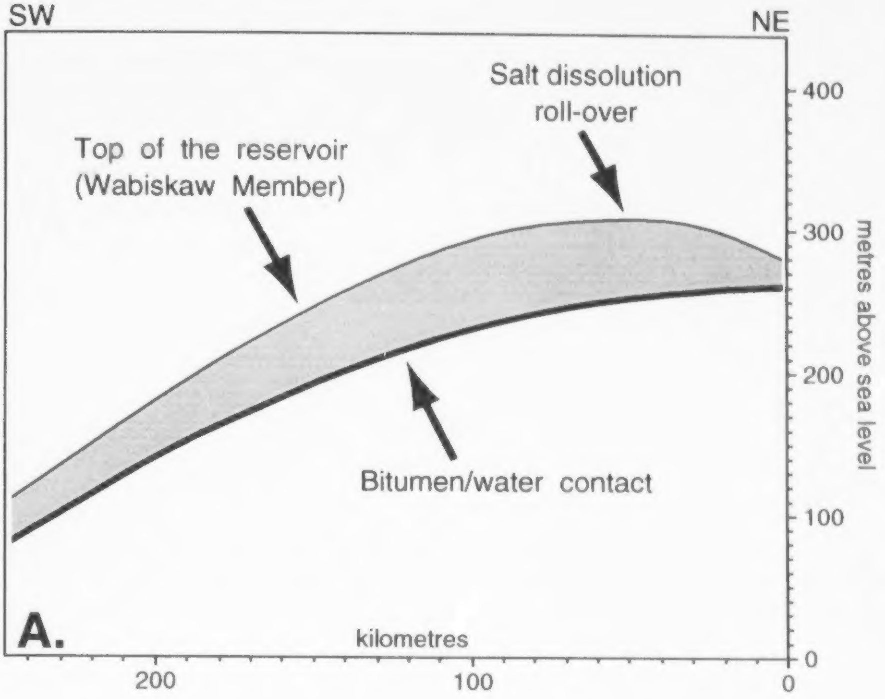
Figure VIII-7

Contour Interval: 5m

Figure VIII-8. Trend surface cross-sections through the Athabasca reservoir, approximately perpendicular to the strike of the Laramide subsidence. For location, see figure VIII-4.

A. Present day configuration of the Athabasca reservoir. Note that the bitumen-water contact dips slightly less than the stratigraphic dip of the host reservoir.

B. The structure of Athabasca reservoir, restored to its configuration at the time of trapping of the oil by flattening the bitumen-water contact. The salt dissolution roll-over formed before migration of the bitumen, thus forming the trap.


SW
NE
Salt dissolution roll-over
Top of the reservoir (Wabiskaw Member)
Bitumen/water contact
A.
kilometres
200
100
0
400
300
200
100
0
metres above sea level

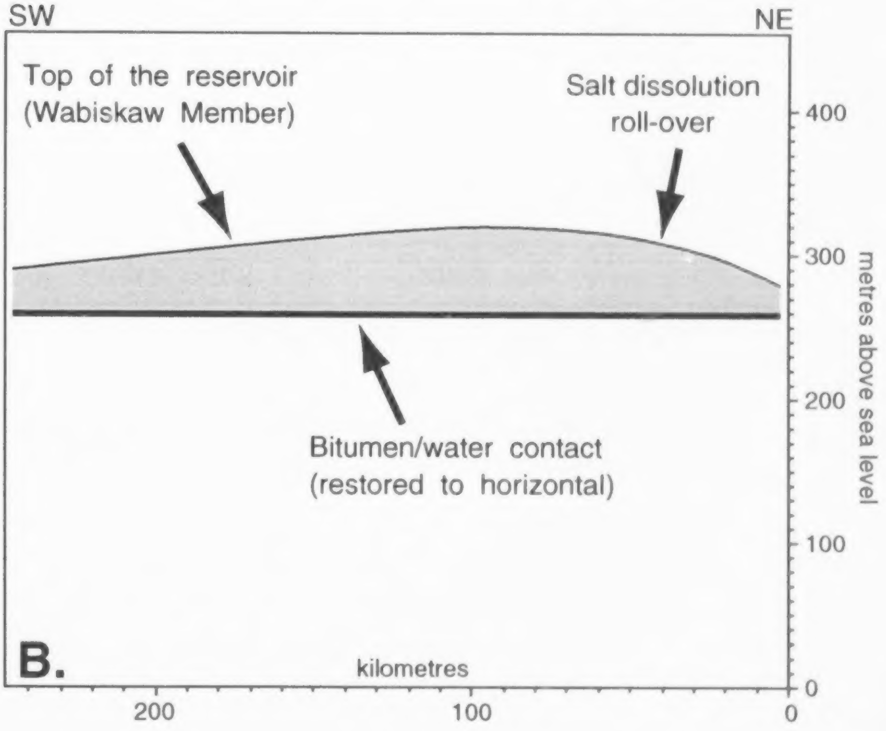
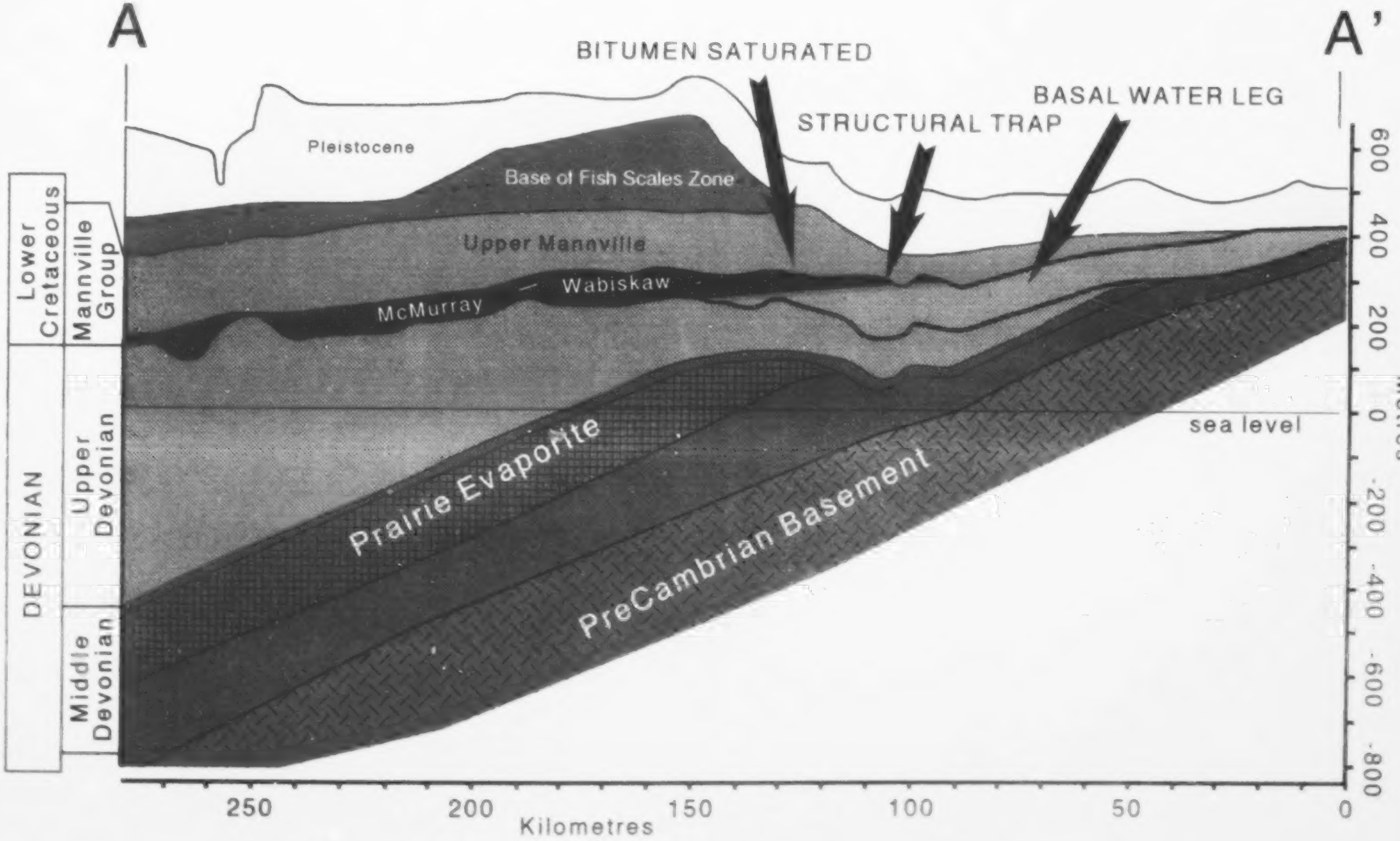
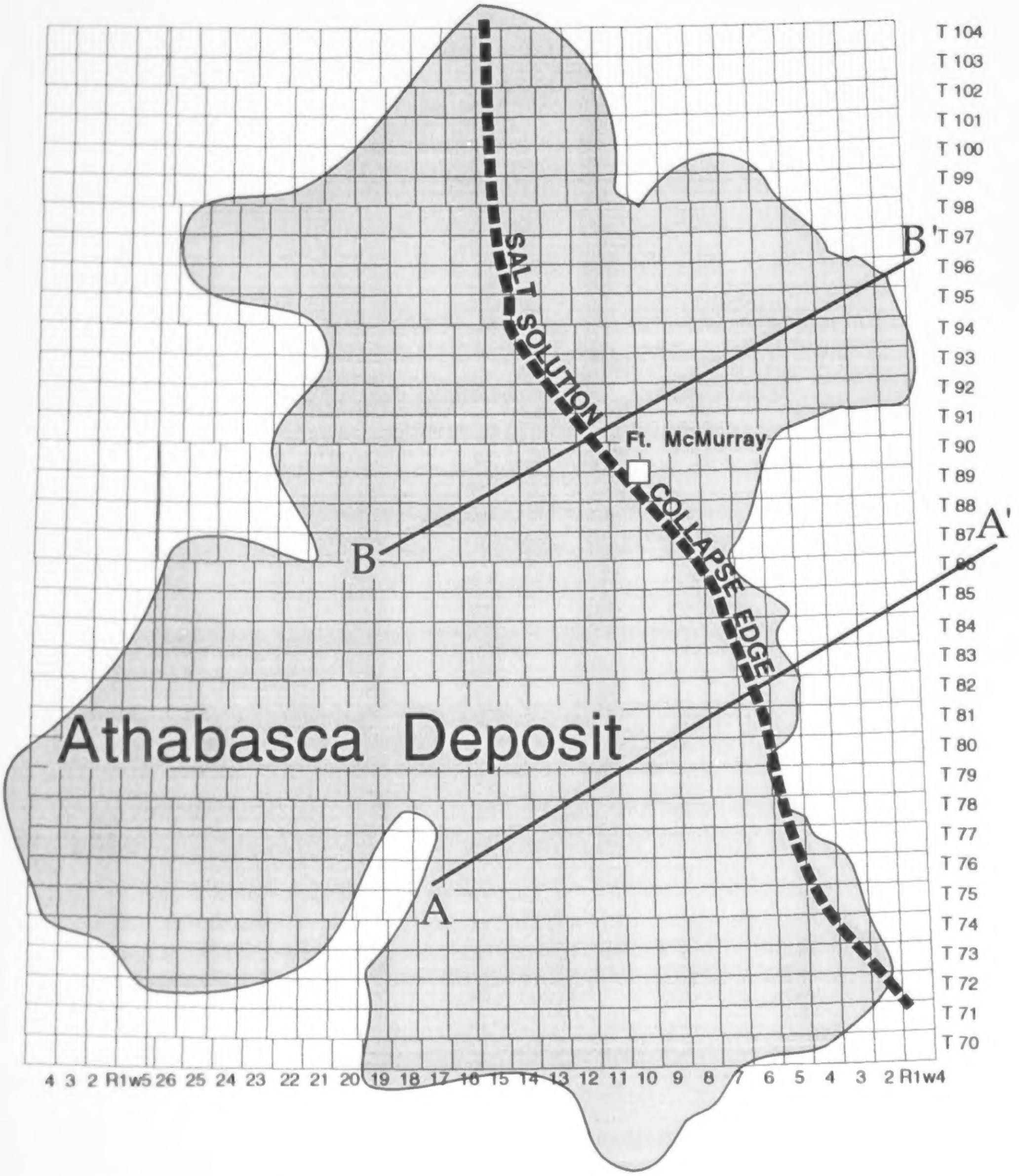

SW
NE
Top of the reservoir (Wabiskaw Member)
Salt dissolution roll-over
Bitumen/water contact (restored to horizontal)
B.
kilometres
200
100
0
400
300
200
100
0
metres above sea level

Figure VIII-9. Structural cross-section through the Athabasca reservoir at location A-A′ (for location, see figure VIII-10). Trapping mechanism along the southeastern edge of the reservoir is structural, and is caused by collapse due to dissolution of Prairie Evaporite salt. Here, structural collapse occurred after deposition of the McMurray-Wabiskaw reservoir rocks, but before migration and trapping.


A
A'
BITUMEN SATURATED
STRUCTURAL TRAP
BASAL WATER LEG
Pleistocene
Base of Fish Scales Zone
Upper Mannville
Wabiskaw
McMurray
sea level
Prairie Evaporite
PreCambrian Basement
Lower Cretaceous
Mannville Group
DEVONIAN
Upper Devonian
Middle Devonian
Metres
600
400
200
0
-200
-400
-600
-800
Kilometres
250
200
150
100
50
0


Athabasca Deposit
SALT SOLUTION COLLAPSE EDGE
Ft. McMurray
A
A'
B
B'
T 104
T 103
T 102
T 101
T 100
T 99
T 98
T 97
T 96
T 95
T 94
T 93
T 92
T 91
T 90
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T 72
T 71
T 70
4 3 2 R1w5 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 R1w4

Figure VIII-10. Outline of the Athabasca Oil Sands Deposit. East of the salt solution edge, structural collapse has produced a roll-over structure that forms the trap in the southern part of the deposit. The northern part of the deposit extends beyond the salt solution edge and was probably stratigraphically trapped. A-A' and B-B' refer to cross-section figures VIII-9 and VIII-12 respectively.

be surmised that it shaled out to the north beyond the present day erosional edge, suggesting the existence of a northern stratigraphic component to the trap.

One problematic area of the trapping mechanism remains. The northeastern limit of the deposit is not explained by structural trapping due to salt solution dip reversal. Bitumen is found far to the east of the present day edge of salt solution collapse (Fig. VIII-10). North of township 90, almost all of the salt dissolution and consequent structural collapse occurred before Mannville time (D. McPhee, pers. comm.). Therefore the Wabiskaw shale that forms the seal is relatively flat and did not experience the dip reversal seen in the south.

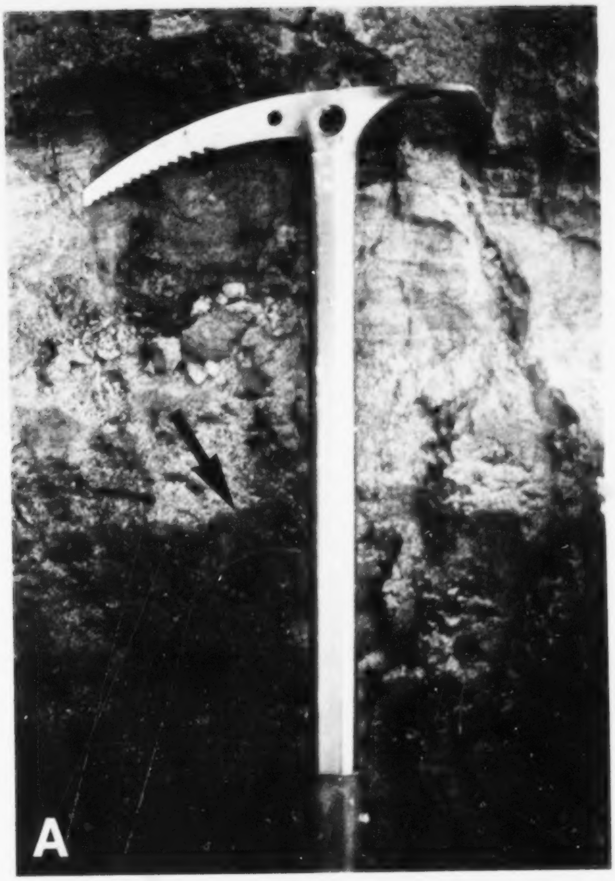
How then was the bitumen trapped in the northeast? There is no evidence that the McMurray Formation shales out towards the east. Furthermore, there appears to be an up-dip gas leg in the area. In outcrops along the Christina River (Fig. VIII-11a), and in nearby wells there are barren sands above the bitumen saturated sands. As discussed above, these can only be evidence of a paleo-gas leg that has leaked off after degradation of the oil and been displaced by water. Additional, circumstantial evidence of the former existence of gas in these barren zones is the presence of sulphur precipitate associated with carbonaceous matter in outcrops of the overlying barren zone on the High Hill River (Fig. VIII-11b). This infers that hydrogen sulphide (a common component of natural gas) was present in the porous sand at some time in its diagenetic history (H. Machel, pers. comm.). This overlying paleo-gas leg means that the bitumen plug trapping mechanism (Mossop, 1980) can be discounted since the gas was updip from the bitumen, shared the reservoir, and would have required a trap of its own. Also the bitumen saturated zone does not end abruptly by laterally interfingering with unsaturated sand as depicted in diagrams of the bitumen plug theory (Mossop, 1980), but it has what would have been a normal density relationship. The barren zone (originally gas) vertically displaces the bitumen as the structural elevation of the reservoir rises (Fig. VIII-11a).

A simple stratigraphic mechanism can easily explain the trap. During transgression of the Clearwater sea, shales overstepped the reservoir sands sealing them by onlap against the Precambrian Shield (Fig. 12). Outcrop

Figure VIII-11.

A. Outcrop of the Athabasca Oil Sands on the Christina River, approximately 3.5 km southeast of where the Christina River joins the Clearwater River. Near the top of the cutbank can be found the contact (arrow) of the bitumen-saturated sand with the now-barren sand of a paleo-gas cap.

B. Outcrop of the McMurray Formation at High Hill River. Yellow precipitate associated with thin carbonaceous laminae is sulphur (arrows), indicating the presence of hydrogen sulphide at some time in the diagenetic history. Hydrogen sulphide is a common component of natural gas, providing circumstantial evidence that the barren sands at High Hill, updip from the Athabasca Oil Sands, once constituted part of an extensive gas cap on top of the bitumen.


A

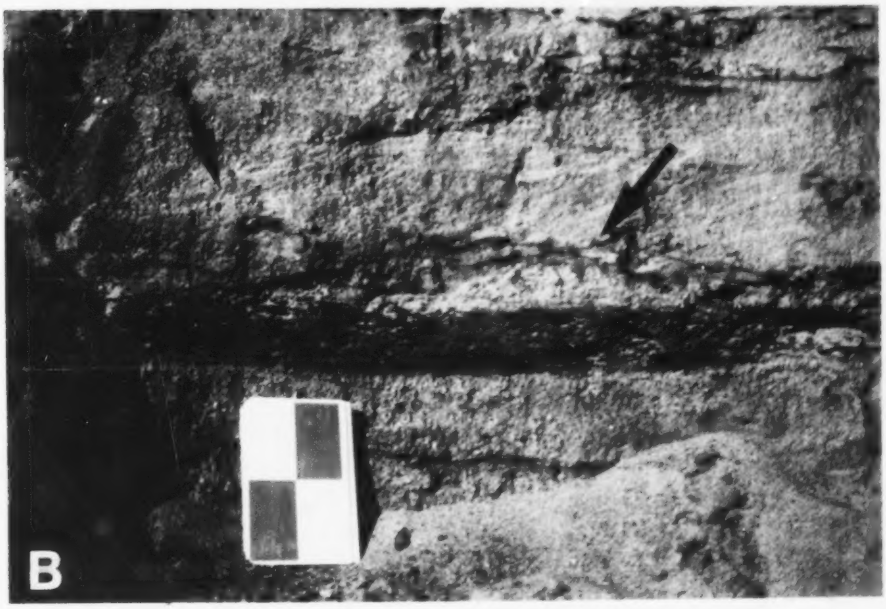
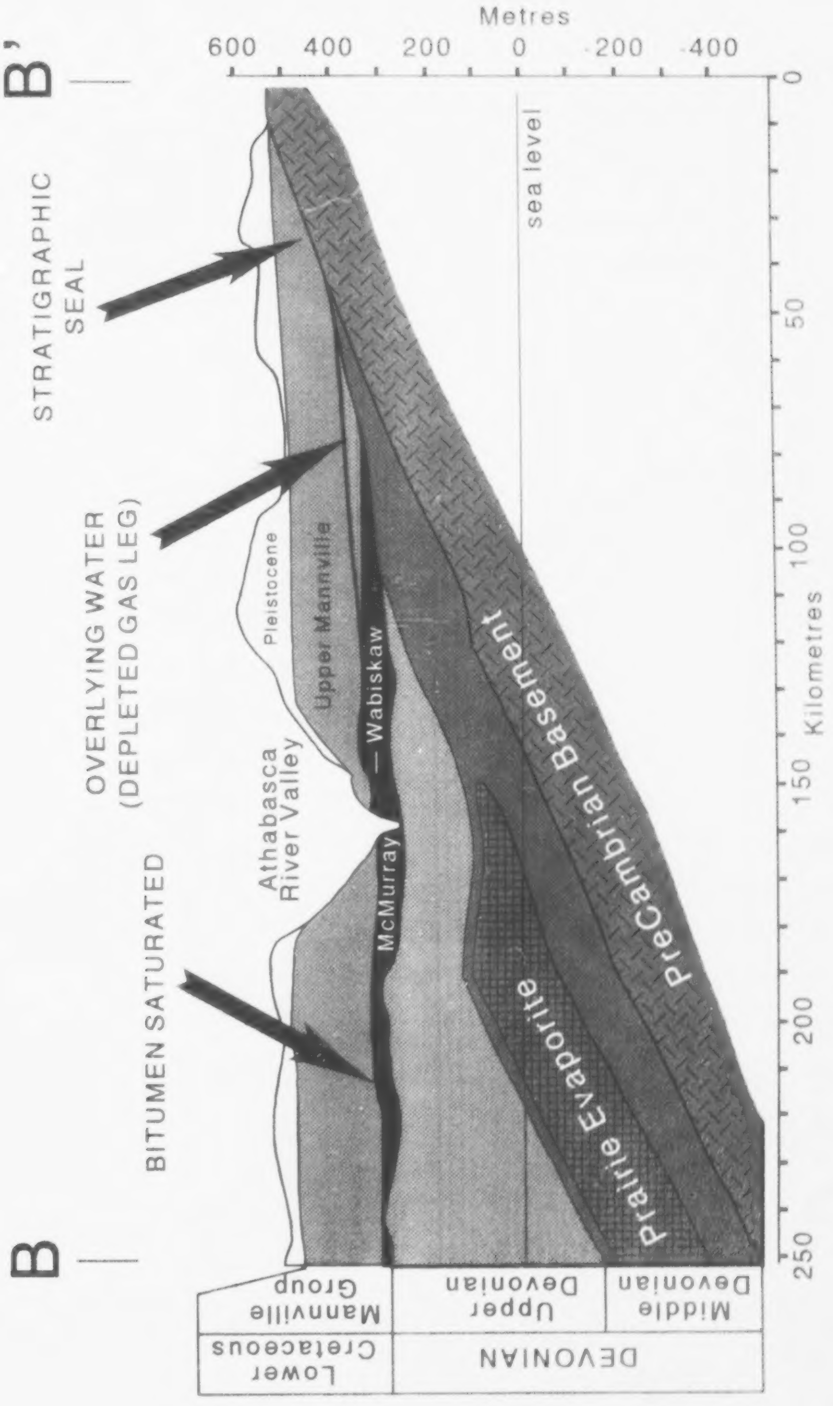

B

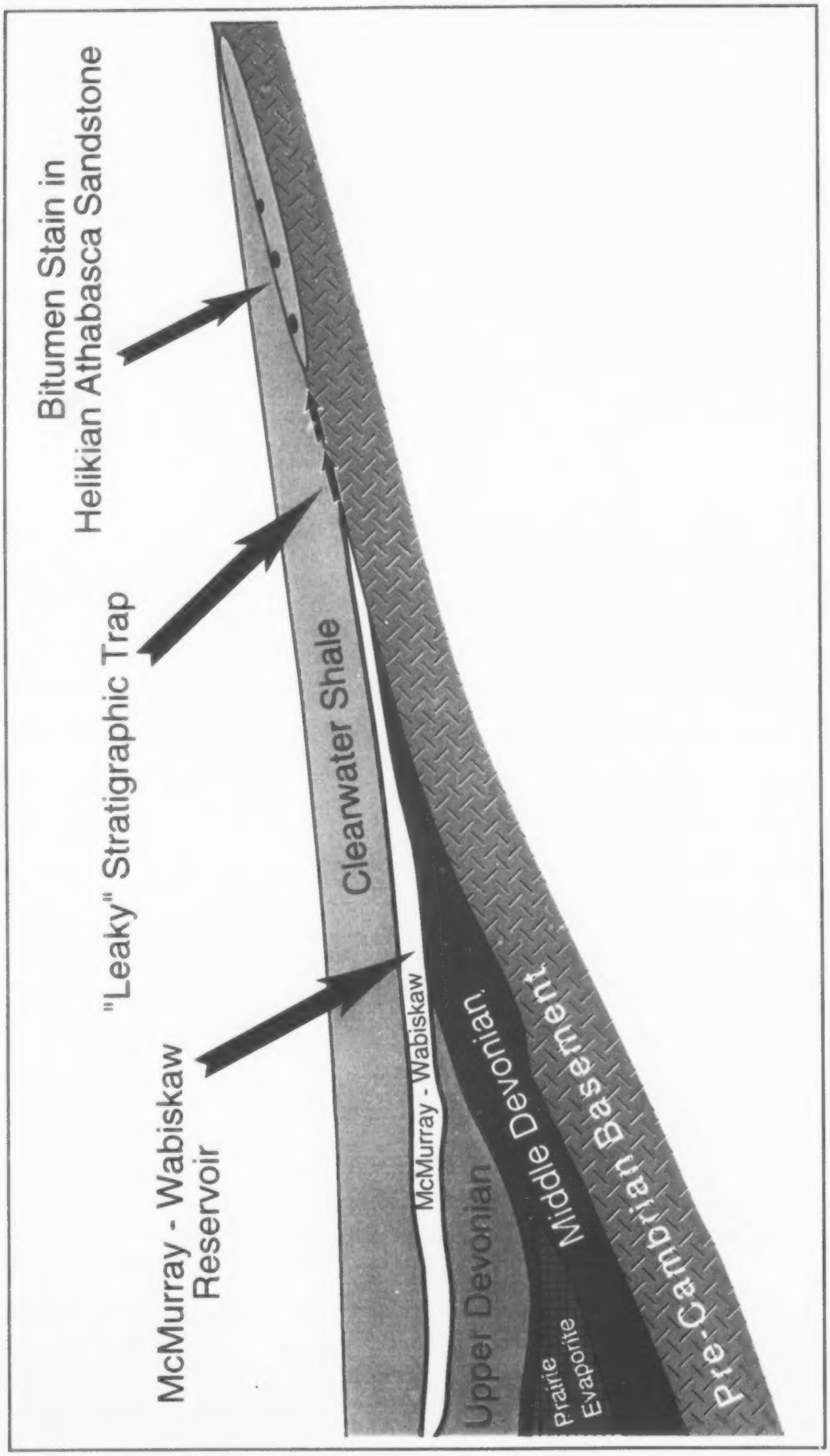
Figure VIII-12. Structural cross-section through the Athabasca reservoir at location B-B′ (for location, see figure VIII-10). Trapping mechanism along the northeastern edge of the reservoir was probably stratigraphic. Upper Mannville Clearwater shale onlapped the Precambrian basement, sealing the reservoir. Structural collapse due to salt dissolution of the Prairie Evaporite occurred before deposition of the McMurray-Wabiskaw reservoir rocks, and therefore did not play a role in the trapping mechanism in the northeast.


B
B'
BITUMEN SATURATED
OVERLYING WATER (DEPLETED GAS LEG)
STRATIGRAPHIC SEAL
Athabasca River Valley
Pleistocene
Upper Mannville
Wabiskaw
McMurray
Prairie Evaporite
PreCambrian Basement
sea level
Metres
600
400
200
0
-200
-400
Kilometres
0
50
100
150
200
250
Lower Cretaceous
Mannville Group
DEVONIAN
Upper Devonian
Middle Devonian

evidence for this no longer exists because erosion at the edge of a tilted basin typically exposes older beds towards the edge and their original configuration is destroyed. If this trapping mechanism was indeed the operative one, one would perhaps not expect a perfect seal at the edge for a number of reasons. First, as the Clearwater Formation transgressed and onlapped the Precambrian Shield it is likely to have left a coarse detrital lag at its base, the thickness of which would depend on the rate of sea-level rise, the angle of incline of the shoreface and the amount of detritus available. Second, any porosity in the Precambrian regolith such as a fracture network or porous clastics could also provide minor conduits through the seal. Either or both of these conditions could have provided a pathway for oil or gas seeps along the edge of the basin, when gas still existed and when the oil was still mobile. It is noteworthy that bitumen is very common in fractures and porous clastics of the Precambrian Athabasca Group and in fractures of older basement. These occur both in outcrop and in boreholes as far away as the eastern shore of Lake Athabasca approximately 150 kilometres northwest of the edge of the Athabasca Oil Sand Deposit (Wilson, 1985). Furthermore, analysis of a single sample of this Precambrian bitumen indicates a composition that compares closely with bitumen from the McMurray Formation (Wilson, 1985, appendix G) but is heavier and presumably more degraded. The amount of bitumen trapped in Precambrian rocks has never been determined, and its extraction potential, if any, is unknown. However its occurrence can be explained as minor seeps through the stratigraphic pinch-out trap of the McMurray Formation against the Precambrian Shield (Fig. VIII-13). One can surmise that much gas also escaped by this route even before the McMurray Formation reservoir was breached by erosion.

South of township 90, where the trapping mechanism is structural due to post depositional roll-over from salt dissolution collapse, it can be conjectured that the existence of this structure was probably not crucial to the trapping mechanism. The same kind of stratigraphic pinch-out of the reservoir, sealed by onlapping shales can be expected further to the east. If anything, the salt solution collapse structure probably restricted the areal size of the trap by many thousands of square kilometres.

Figure VIII-13. Schematic of the proposed stratigraphic trapping mechanism in the northeast of the Athabasca Oil Sands. The Clearwater shale did not provide a perfect seal against the Precambrian regolith. The presence of bitumen stain in the Helikian Athabasca Sandstone, updip from the Athabasca Oil Sands, suggests the trap was quite "leaky". The extent of the Precambrian bitumen reserves is unknown, but has been observed filling fractures and pores in cores recovered during uranium exploration.


McMurray - Wabiskaw
Reservoir
"Leaky" Stratigraphic Trap
Bitumen Stain in
Helikian Athabasca Sandstone
Clearwater Shale
McMurray - Wabiskaw
Upper Devonian
Middle Devonian
Prairie
Evaporite
Pre-Cambrian Basement

Timing

The southwestern dip of the bitumen-water contact is only slightly less than regional structural dip of the Lower Cretaceous strata (Fig. VIII-8). This dip is due to subsidence of the foreland basin that was caused by Laramide uplift and subsequent tectonic and sediment loading. Since the immobilised bitumen-water contact has experienced all but a small part of this subsidence, it can be concluded that migration, trapping and degradation all were completed very early in Laramide time. Tectonic studies of the western part of the basin suggest that the earliest effects of the Laramide orogeny were felt in Late Cretaceous time (Porter *et al.*, 1982). It is difficult to estimate a more exact upper limit for the time of final immobility of the oil-water contact.

The top of the Colorado Group, a distinctive and therefore convenient horizon (approximately the beginning of the Campanian, mid-Late Cretaceous), may be used as an estimate of the time of peak generation and migration of oil. The basin configuration can then be restored to an approximation of its configuration at the time of trapping by flattening the top of the Colorado Group (compare Fig. VIII-14 to Fig. VIII-14).

The Upper Cretaceous limit on the formation of the oil may also explain the apparent present day volume deficit of source rocks for the oil sands of western Canada. Pre-Laramide palinspastic reconstruction of the western Canada basin (McMechan and Thompson, 1992; Gabrielse and Yorath, 1992) provides evidence of a much larger potential volume of source rocks than would have been available later in the history of the Laramide orogeny, when thrust and translational tectonics shortened the foreland belt by up to 200 km (Gabrielse and Yorath, 1992), removing much potential source from the hydrocarbon "kitchen".

It seems apparent from this study that the formation, migration, trapping and degradation of the Athabasca bitumens must have been all but completed early in the development of the Laramide orogeny, by Late Cretaceous time. However, the onset of oil formation could not have begun much earlier than this time, because the burial history of the basin indicates that conditions were inadequate (Deroo *et al.*, 1977). It follows therefore that the vast volumes of oil required to produce the Athabasca bitumen (not to mention the other large oil sands and heavy oil deposits) appear to have

Figure VIII-14. Present day structural cross-section from the Alberta foothills to the Precambrian Shield just east of the Athabasca Oil Sands Deposit, drawn perpendicular to the strike of the Laramide subsidence. See cross-section location in figure VIII-1.

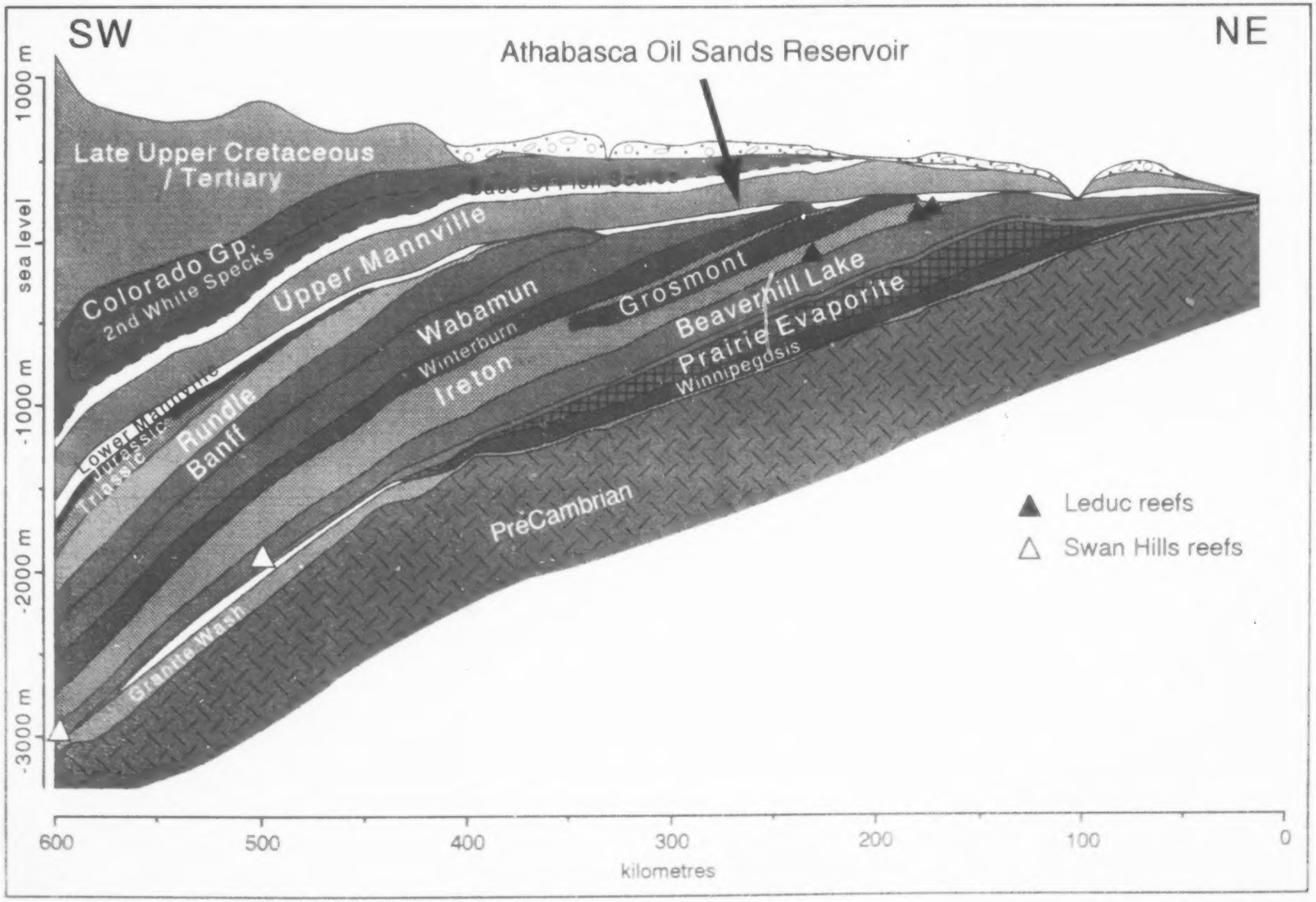
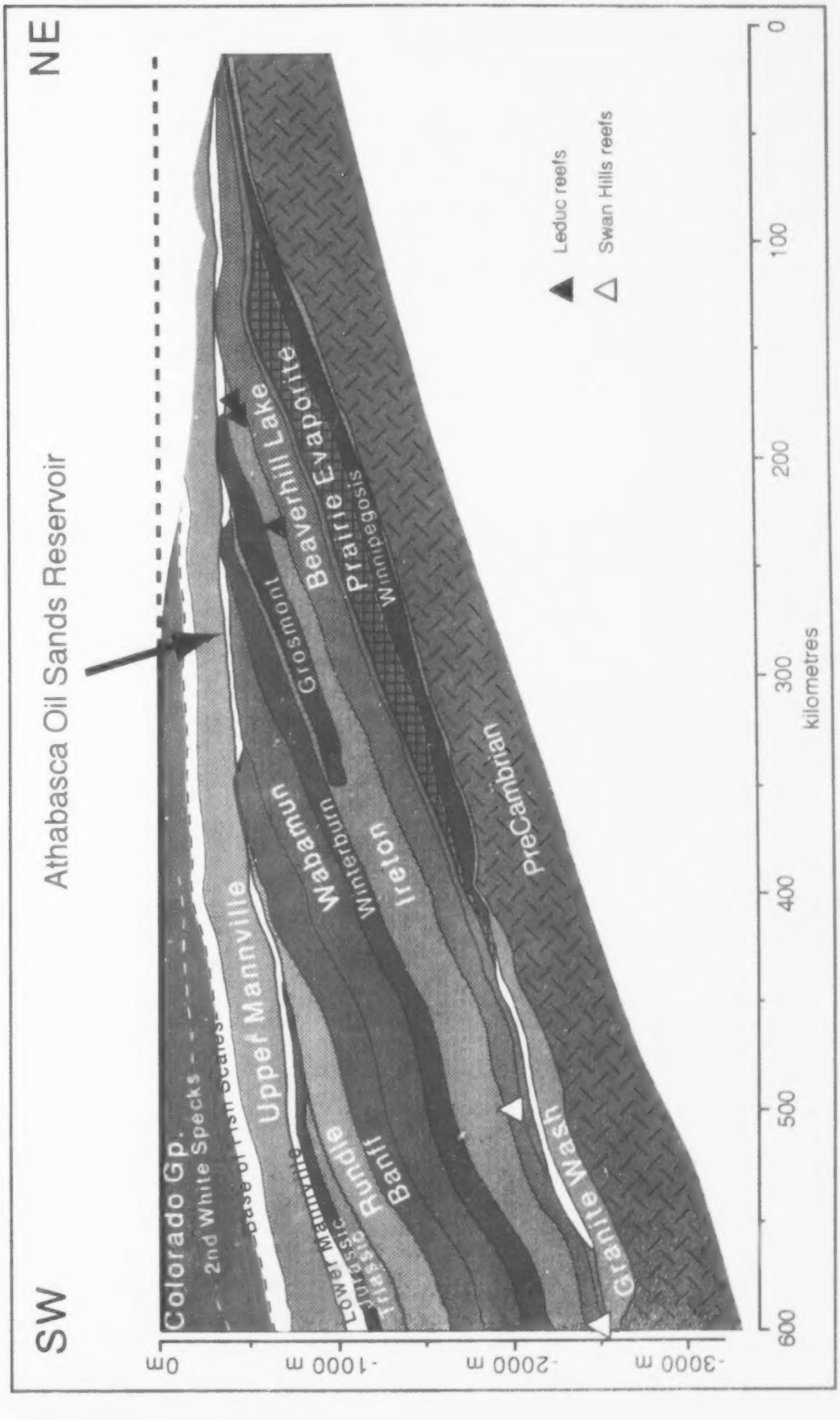

SW
NE
Athabasca Oil Sands Reservoir
1000 m
sea level
-1000 m
-2000 m
-3000 m
Late Upper Cretaceous / Tertiary
Base Of Fish Scales
Colorado Gp.
2nd White Specks
Upper Mannville
Lower Mannville
Jurassic
Triassic
Rundle
Banff
Wabamun
Winterburn
Ireton
Grosmont
Beaverhill Lake
Prairie Evaporite
Winnipegosis
Granite Wash
PreCambrian
▲ Leduc reefs
△ Swan Hills reefs
600
500
400
300
200
100
0
kilometres

Figure VIII-15. Structural cross-section from the Alberta foothills to the Precambrian Shield just east of the Athabasca Oil Sands Deposit, drawn perpendicular to the strike of the Laramide subsidence. Structure is flattened on the top of the Colorado Group (mid-Late Cretaceous) to show an approximation of the basin configuration at the time of migration, trapping and degradation. For cross-section location see figure VIII-1.


SW
NE
Athabasca Oil Sands Reservoir
Colorado Gp.
2nd White Specks
Base of Fish Scales
Upper Mannville
Lower Mannville
Jurassic
Triassic
Rundle
Banff
Wabamun
Winterburn
Ireton
Grosmont
Beaverhill Lake
Prairie Evaporite
Winnipegosis
PreCambrian
Granite Wash
Leduc reefs
Swan Hills reefs
0m
-1000 m
-2000 m
-3000 m
600
500
400
300
200
100
0
kilometres

been generated and to have migrated in a relatively short period of time. An explanation for the rapid migration over many hundreds of kilometres of the huge volumes of hydrocarbon required is beyond the scope of this paper, however it should be noted that time may not be a critical factor for the maturation of organic matter into hydrocarbon. Price (1983) has concluded that beyond about one million years, time is not a factor in organic metamorphism. That is, once temperature and pressure conditions reach critical levels, organic metamorphism is relatively instantaneous (on the scale of geologic time).

Restrictions on Migration Timing and Mechanism

Very early in the Laramide orogeny, significant Cordilleran hydraulic head could not have been present at the time of migration and therefore the large scale, basin groundwater flow of Garven (1989) and Hitchon (1984) could not have been significant at this time. Thus migration was probably driven by compaction and buoyancy. Furthermore, the time window for migration did not extend into the Tertiary as proposed by Garven (1989), but was finished by Late Cretaceous time.

These conclusions have implications and raise more questions regarding the method of oil migration. Specifically, if the oil migrated by buoyancy, then migration as a separate phase is probably indicated rather than as a miscible phase where migration is more easily accomplished by hydrodynamic flow. Here as well, further discussion of this topic is beyond the scope of this paper, but any discussion of migration methods and phases must take into account the conclusion borne out by this study regarding timing of migration and structural attitude of the basin.

Gas

Large and small gas accumulations that share the bitumen reservoirs are common in the Athabasca Deposit. The largest fields are concentrated along the southeastern edge of the deposit, extending beyond the eastern limit of the bitumen.

Some of the gas was possibly formed biogenically in-situ at an early stage (Deroo *et al.*, 1977), and filled small structural anomalies in the Athabasca reservoir. However, potential source rocks would not have been entirely horizontal during the early Laramide, and they probably dipped down through immature to mature to overmature windows of organic metamorphism. Therefore gas could have formed downdip from the zone of contemporaneous oil formation.

The existence of large gas accumulations beyond the eastern limit of the bitumen (Fig. VIII-16) may be evidence for a phase of late gas generation. This area would have been downdip on the structural trap at the time of bitumen accumulation. However subsequent Laramide tilting of the structure has created new structural traps into which the degraded bitumen could not migrate. Any late generation of gas could then accumulate in this updip position of the tilted anticlinal structure.

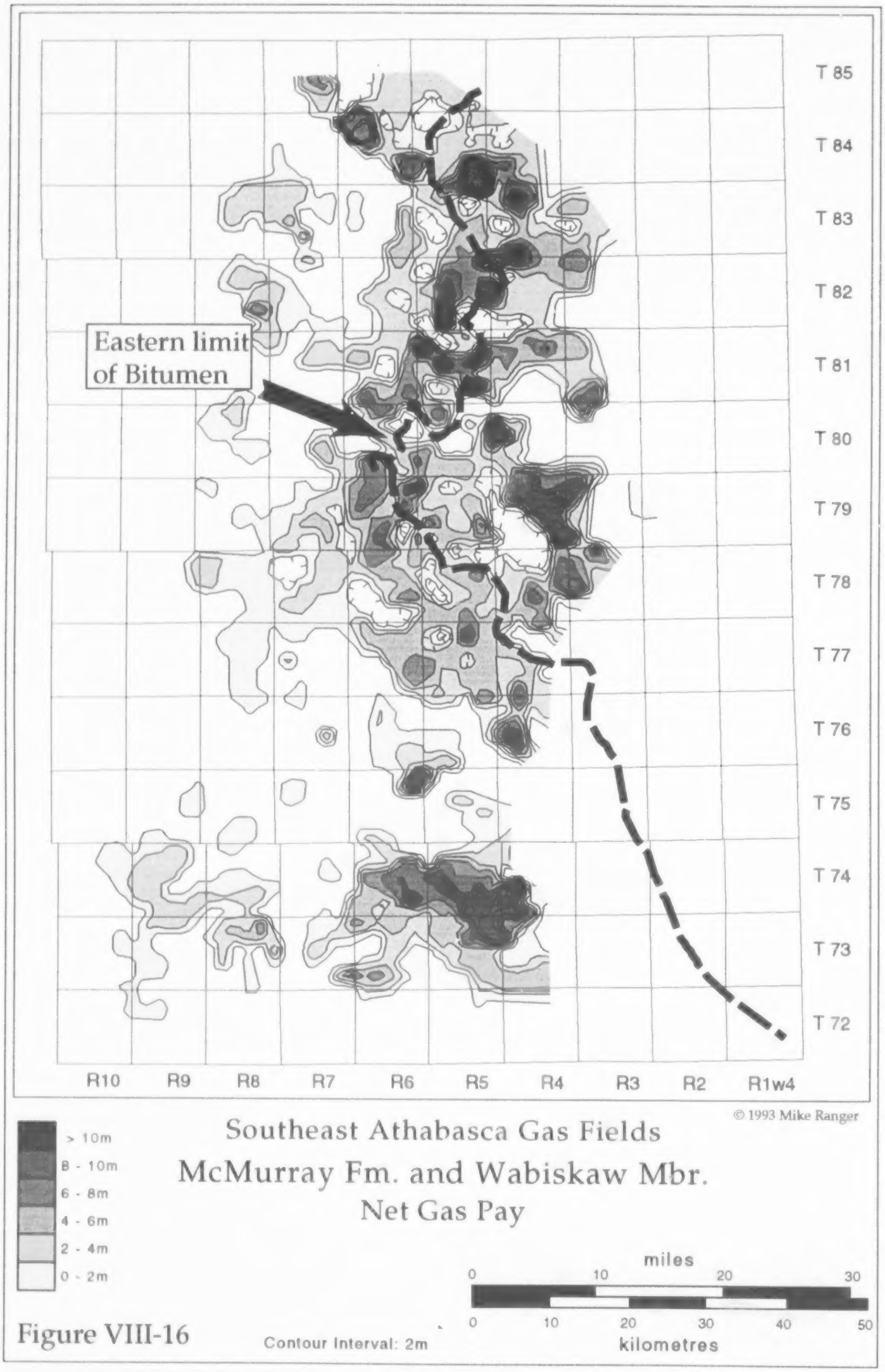
CONCLUSIONS

1- The bitumen-water contact dips to the southwest, parallel to Laramide foreland basin subsidence, but at a slightly lesser angle than the reservoir host strata. This indicates early generation, trapping and degradation of bitumen, probably no later than Late Cretaceous.

2- The migration mechanism must have been dominantly gravity/density and buoyancy because little hydraulic head existed in the Cordillera early in the Laramide orogeny.

3- The trap is a simple shallow anticlinal structure but of tremendous areal size. A major stratigraphic component is important in the northeast, where the trap probably consisted of a leaky seal of Clearwater shales onlapping the Precambrian regolith.

4- There were several episodes of gas accumulation, filling the reservoir at different stages of its structural development. The major gas fields along the southeast edge of the Athabasca Oil Sands Deposit are charged with early generated gas where associated with the bitumen, and the fields that lie beyond the eastern edge of the bitumen may contain late generated gas that filled a later configuration of the trap.


Eastern limit of Bitumen
T 85
T 84
T 83
T 82
T 81
T 80
T 79
T 78
T 77
T 76
T 75
T 74
T 73
T 72
R10
R9
R8
R7
R6
R5
R4
R3
R2
R1w4
> 10m
8 - 10m
6 - 8m
4 - 6m
2 - 4m
0 - 2m
miles
0
10
20
30
0
10
20
30
40
50
kilometres
Contour Interval: 2m

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Southeast Athabasca Gas Fields
McMurray Fm. and Wabiskaw Mbr.
Net Gas Pay

Figure VIII-16

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CHAPTER IX

A RESOURCE INVENTORY OF THE OIL SANDS OF SOUTH ATHABASCA

INTRODUCTION

In the course of a stratigraphic and sedimentological study of the south Athabasca Oil Sands Deposit, a large database of digitised geophysical well logs was acquired. Although its primary purpose was not of a geotechnical nature, one obvious use of such data is to characterise the hydrocarbon resources and the economic potential of the reservoir. The data reside on a microcomputer system, and a series of a custom-written programs was produced to extract the required information and prepare it for mapping.

The large number of wells used in this study, a maximum of 1 per section, provides a more detailed look at the reservoir than any previous study. Recent reviews of the reservoir character of the south and central Athabasca Deposit (Keith *et al.*, 1988; MacGillivray *et al.*, 1989) have restricted their data density to 4 wells per township.

The definitive study of the oil sand resources of the northern part of the Athabasca Deposit is that of Flach (1984). This study also established the standard criteria required to adequately describe the economic character of the Athabasca reservoirs. The maps accompanying Flach's 1984 study have also become the standard method of displaying the pay, sand and water data. Flach concludes that when the basic screening criteria are mapped, the areas suitable for any particular recovery process can be quite limited (Flach, 1984). The present study uses most of Flach's criterion and mapping methods to characterise the resource in south Athabasca.

DATA

The study area covers 21 townships (70 to 90) and 20 ranges (1 to 20 west of the 4th meridian) entailing 15,120 square miles (38,707 square kilometres). From this area approximately 1800 wells at a maximum density of 1 well per section were incorporated into a data base. Several experimental recovery and production areas have very closely spaced wells, not uncommonly on the order of a few hundreds of metres, which would give data resolution that is unnecessary for a regional analysis. Of the selected wells, geophysical logs from approximately 1700 wells were suitable for digitisation.

Geophysical Well Logs

Three curves from each well were digitised, the deep resistivity, the density and the gamma ray. The deep resistivity is useful for delineating hydrocarbon-bearing zones and, in conjunction with the density log, tight zones. The deep resistivity tool, while having less resolution than the shallow or medium reading resistivity tools, is nonetheless preferred in order to minimise erroneous readings from possible formation damage due to drilling. The density log is used primarily to measure porosity, and is also useful for determining gas-bearing zones and coal. The gamma ray log is the preferred tool for basic lithology determination. The SP log may also be used for this purpose, however the spontaneous potential response depends on the presence of permeability and a conductive formation fluid, normally saline formation water, which has an ion potential different from the drilling fluid. In oil sands areas, reservoirs are commonly thoroughly saturated with bitumen over wide areas, which is of course non-conductive, and which normally plugs the pores giving extremely low permeabilities. This attenuates the SP response, and this tool is therefore not as useful as the gamma ray for lithology determination in oil sands deposits.

The digitised logs were used to obtain mappable parameters such as net sand, pay thicknesses, and bottom water determination. In addition, the digitised log database permits automatic and rapid construction of cross-sections in any direction or for any combination of wells desired. This is extremely valuable not only for helping to the visualise the three dimensional configuration of this very large reservoir, but also for quickly testing geological ideas by producing any number of cross-sections through geologically interesting features. Hand drawn cross-sections are tedious and time consuming to produce, and therefore it is not practical to create them in large numbers.

Drill Stem Tests

Drill stem tests are another source of subsurface data. However, because of the immobility of the bitumen, their primary use is as an indicator of the presence of gas. Gas can be detected on geophysical logs using the formation density - sidewall neutron logs. Crossovers formed by zones of low density, accompanied by low concentrations of hydrogen indicate the presence of gas. However many wells do not have neutron logs, and in these the presence of gas is difficult to detect. Solution gas is also difficult to detect from geophysical logs. Drill stem test data therefore provide a direct method for the detection of gas. These data were used to augment the geophysical log indicators to produce the net gas maps for the Wabiskaw/McMurray interval.

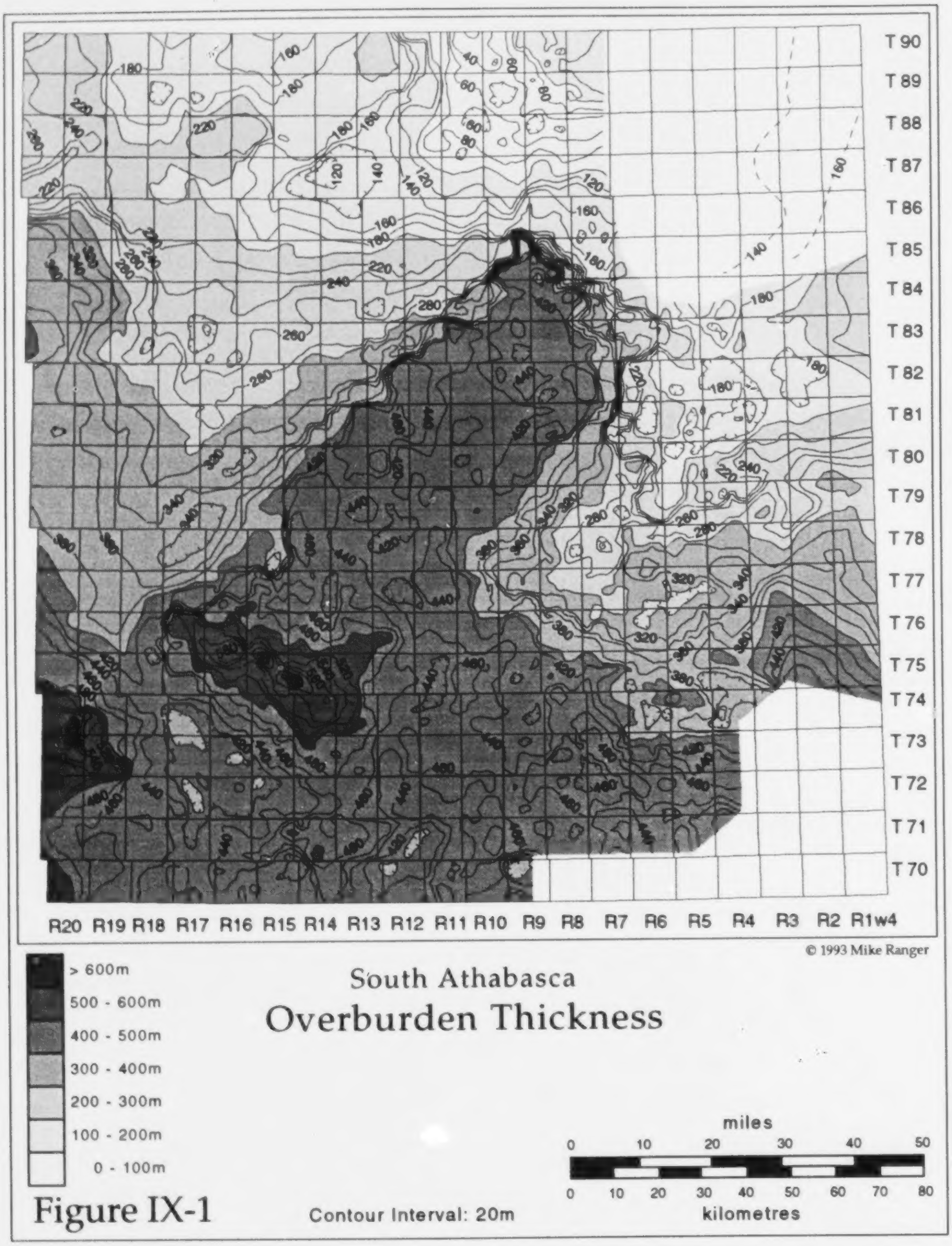
RESERVOIR CHARACTERISATION

Overburden Thickness

Overburden includes all of the strata from surface to the top of the Wabiskaw - McMurray reservoir units (Fig. IX-1). In general this thickness increases from zero in the north where it crops out along the Athabasca River valley to over 620 metres in the southwest in township 74 range 20W4. The thickness of overburden is a critical first order classification of any recovery site, since it determines the basic method of recovery, surface mining or *in situ* techniques.

Surface mining at present is generally restricted to areas with 50 metres or less of overburden. The economic limit may ultimately extend to areas with up to 75 m of overburden (Jardine, 1974; Houlihan and Evans, 1989). The volume of barren overburden that must be removed before mining can proceed determines the economic limit. In the south Athabasca area only a very small area lies within even the 75 m limit. This is along the Athabasca River valley in the north in townships 88 to 90 and ranges 8 to 10W4. This area mostly underlies the town of Ft. McMurray and its surrounding inhabited areas, and thus is never likely to be exploited.

It therefore appears that virtually all of the south Athabasca Oil Sands Deposit will require an *in situ* method for recovery. *In situ* methods are techniques that heat the formation to lower the viscosity of the bitumen. At formation temperatures the bitumen is immobile and typically has a viscosity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T 74
T 73
T 72
T 71
T 70
R20 R19 R18 R17 R16 R15 R14 R13 R12 R11 R10 R9 R8 R7 R6 R5 R4 R3 R2 R1w4
> 600m
500 - 600m
400 - 500m
300 - 400m
200 - 300m
100 - 200m
0 - 100m
miles
0 10 20 30 40 50
0 10 20 30 40 50 60 70 80
kilometres

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South Athabasca

Overburden Thickness

Figure IX-1

Contour Interval: 20m

of over one million centipoise (cP). Increasing the temperature to 100°C lowers the bitumen viscosity to below 1000 cP allowing it to become mobile (Ali and Verma, 1989). Some minimum thickness of overburden is required to contain the pressures of steam stimulation or combustion. The thickness required is thought to vary between 150 to 200 m (Janisch, 1979; Allen, 1979). Fireflooding operations have been underway for many years in the Gregoire Lake area, which has overburden as thin as 160 m. For some low pressure methods of preheating such as electric heating, or the use of horizontal wells (Ali and Verma, 1989), minimum overburden thickness could be much less, possibly as little as 50 m, depending on the nature of the overlying seal and the pressures required for the steamflood or fireflood operation used to recover the bitumen after the preheat (Flach, 1984). Overburden thickness may also be vital for the propagation and orientation of fractures that ease fluid communication between wells. Flach (1984) discusses the relationship of fracture geometry with depth, suggesting that 300 to 450 m may be a practical lower limit for relying on horizontal fractures to achieve fluid communication.

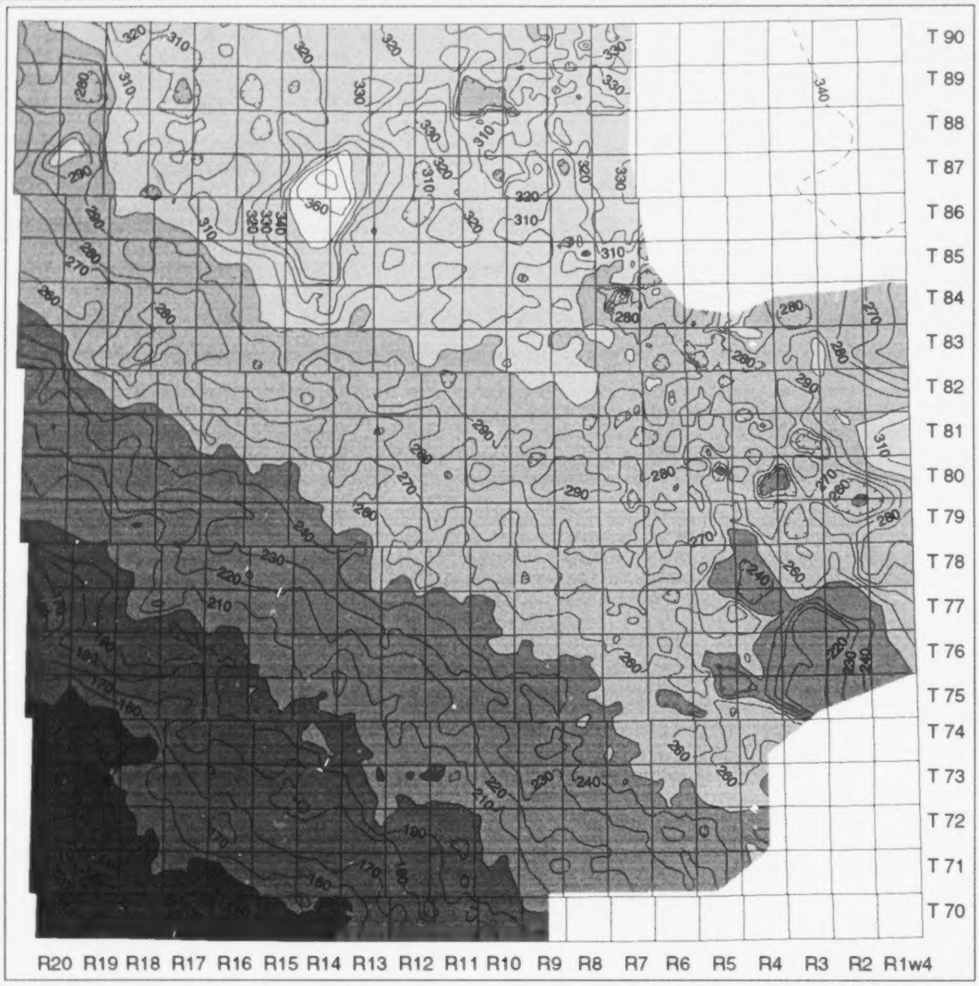
Structural Elevation of the Top of the Reservoir

The top of the Wabiskaw Member of the Clearwater Formation is a persistent regional shale with a very distinct resistivity marker. This marker is everywhere within a few metres of the top of the reservoir, and its structural elevation is shown in Figure IX-2.

The present day structural orientation of the basin includes a first order structural tilt to the southwest. This structural tilt is a consequence of the Late Cretaceous-Tertiary Cordilleran Laramide orogeny.

The effect of structural collapse due to dissolution of underlying salt is also evident on the eastern edge of the McMurray subbasin. Dissolution took place sporadically and continues to the present day as evidenced by the occurrence of saline springs in the area north of Fort McMurray.

The structural collapse expresses itself as a broad reversal of trend, which constitutes part of the structural trapping mechanism for the hydrocarbons. Superimposed on this trend are several local areas of anomalous lows in the structure, some elongate and some apparently more equidimensional. These


T 90
T 89
T 88
T 87
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R1w4
360
340
330
320
310
300
290
280
270
260
240
230
220
210
180
170
160

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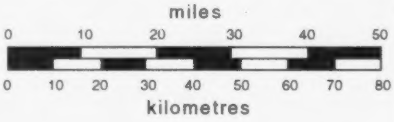
- ▢ 350 - 400m
- ▢ 300 - 350m
- ▢ 250 - 300m
- ▨ 200 - 250m
- ▨ 150 - 200m
- ■ 100 - 150m

South Athabasca

Structural Elevation
Top of Wabiskaw Member


miles
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70
80
kilometres

Datum: sea level
Contour Interval: 10m

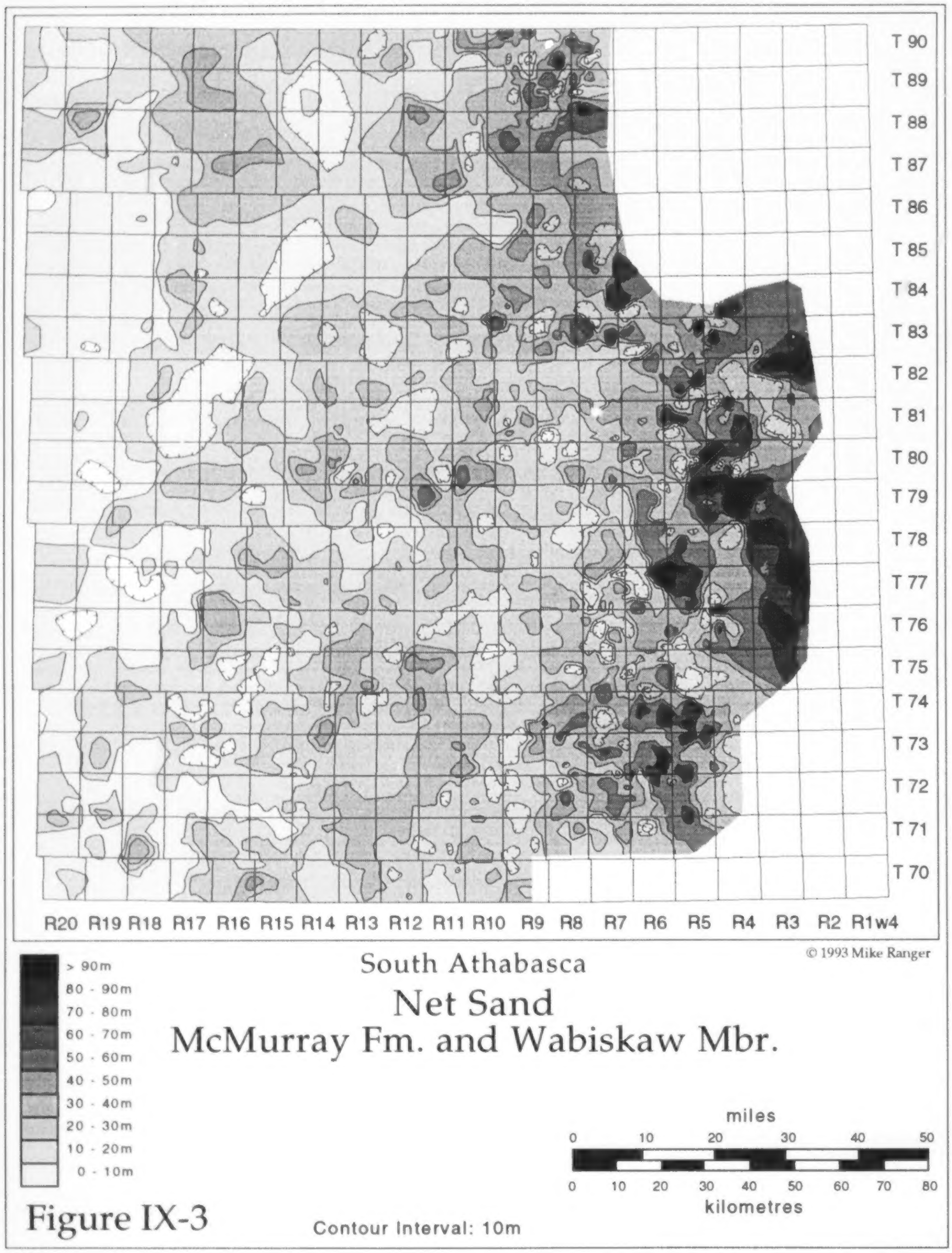
Figure IX-2

indicate areas of more advanced salt solution probably because these are areas which allow easier access to circulating solutions due to faulting. Because these structures are expressed on the top of the Wabiskaw Member, they must be interpreted as younger than the Wabiskaw. If they were older they presumably would have been filled in during deposition. This is not to say that some of these areas may not have experienced structural collapse before or during deposition as well as the collapse that is evidently post depositional. The existence of pre-depositional and syndepositional structural collapse can often be distinguished on isopach maps of the Wabiskaw-McMurray interval that show anomalous thickening, although it may not always be possible to distinguish such anomalies given the relatively rough nature of the topography and associated fill. This is especially so in areas of poor well control, and the well control generally falls off rather quickly east of the salt dissolution edge because of the lack of bitumen reserves.

The structural reversal in dip over the salt dissolution edge is known as the Athabasca anticline. The Athabasca anticline has been recognised as the largest such hydrocarbon bearing structure in existence (Masters, 1984). This structure can be followed south of the Athabasca area to the Cold Lake Deposit and into the heavy oil fields of the Lloydminster area. Its axis is generally parallel to the salt solution edge, which constitutes its eastern flank, but it may have a modern day component that extends southward to the Sweetgrass Arch (Masters, 1984).

Net Sand

Total net sand (Fig. IX-3) was calculated for 1520 wells from the gamma-ray geophysical log. The method used is to apply a simple cutoff to the gamma-ray response. Because gamma-ray logs are often miscalibrated or calibrated to different standards, and their resolution varies with the logging speed, an empirical method is typically utilised to obtain a cutoff response. A plateau of high readings indicates the pure shale response or "shale line", while a set of consistent low readings is taken to indicate clean quartz sand, known as the "sand line". Anywhere from 50 to 70% of this response range is chosen as the "shale cutoff" (Asquith, 1982). Intervals with gamma-ray response lower than the cutoff are summed to calculate net sand. By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80 - 90m
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60 - 70m
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40 - 50m
30 - 40m
20 - 30m
10 - 20m
0 - 10m
miles
0 10 20 30 40 50
0 10 20 30 40 50 60 70 80
kilometres

South Athabasca

Net Sand

McMurray Fm. and Wabiskaw Mbr.

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Figure IX-3

Contour Interval: 10m

calibrating the gamma-ray response to core it was determined that a cutoff of 50% of the range produced the most reliable estimates of net sand in this study. The reliability of this method rests primarily on the accuracy with which the clean sand response is determined, since there may not be much clean sand in the interval. On the other hand, a Clearwater shale marker bed immediately above the Wabiskaw Member provides an regionally persistent shale marker bed that can be used as a consistent shale line. The net sand maps produced from this method are generally optimistic as an indicator of reservoir quality, since a gamma-ray response that barely makes the cutoff may indicate considerable shale in the sand, or the presence of shale beds that are thinner than the resolution of the gamma-ray tool. In addition, the absence of porosity normally has little or no effect on the gamma-ray response.

The thickness of net sand is somewhat correlated to the thickness of the entire interval, however there is considerable variance due to the distribution of facies. Generally the area with the most net sand is in the eastern edge of the basin where thick, sand-filled, fluvial channels dominate.

RESERVOIR FLUIDS

Bitumen

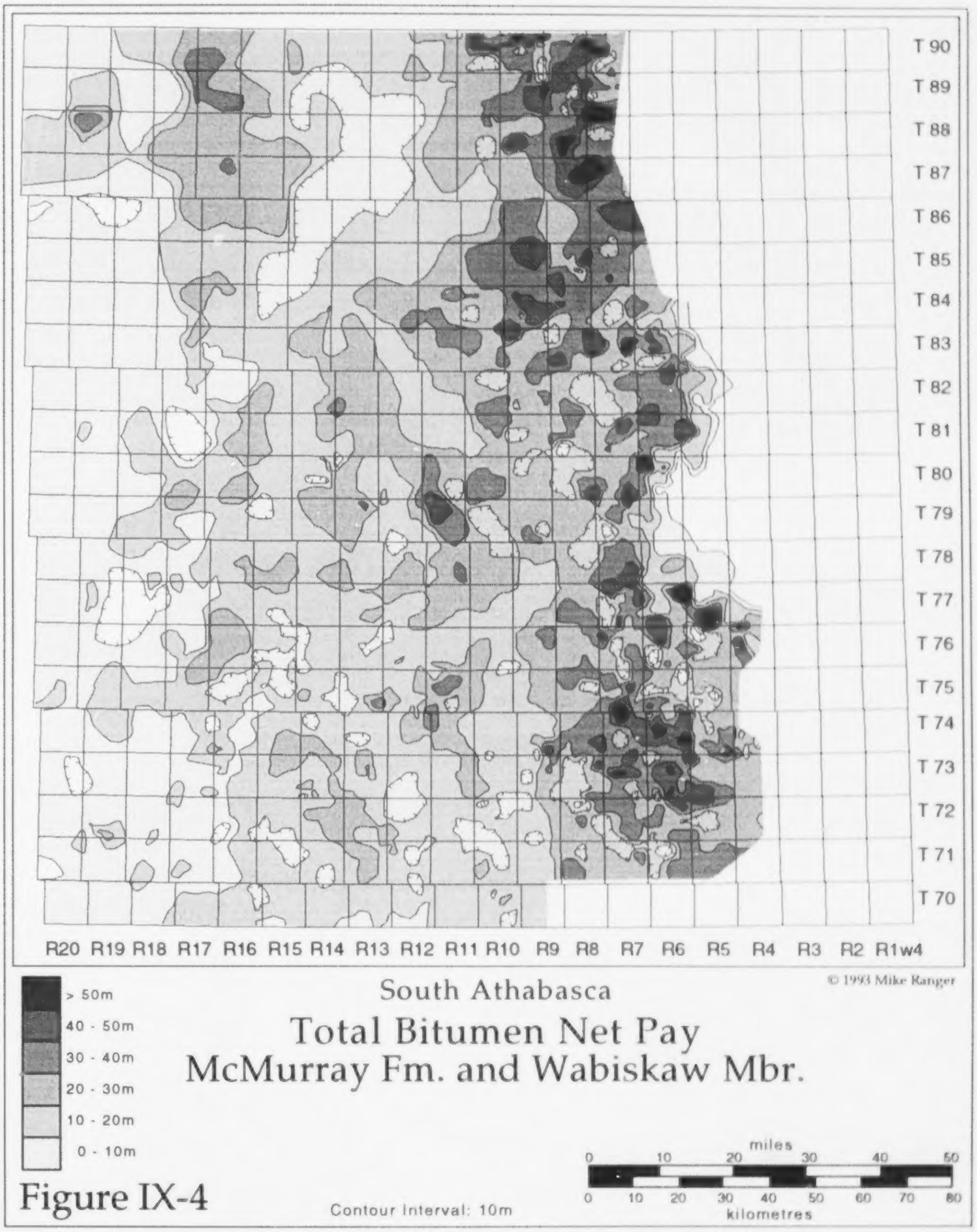
Calculating net pay from the resistivity logs is less empirical that the method for calculating net sands. In any area a fixed resistivity cutoff can be used as a direct measure of weight-percent bitumen saturation in a clean sand if the porosity and the resistivity of the formation water are known or can be estimated. Reservoir sands in the Athabasca Deposit tend to have little diagenetic overprint, and porosities tend to be consistent between 30 and 35% by volume. However the resistivity of the formation water depends on the salinity of the formation water, and this can pose a problem in the Wabiskaw-McMurray strata, especially where they are shallow. Influx of meteoric fresh water can cause fluctuating formation salinities, even where the regional salinity patterns are known. Fortunately this problem tends to occur more in north Athabasca where much of the reservoir is very close to surface. Furthermore, it is common to perform detailed analysis on cored tar sands exploratory wells to determine porosity and weight percent bitumen saturation. This analysis can be used to directly calibrate the resistivity log even if the reservoir resistivity is unknown. The economic resistivity cutoff can then be extrapolated to nearby wells that are not cored. This procedure was used to produce the various pay maps, all of which represent bitumen saturations greater than or equal to 6 weight percent.

Net Bitumen Pay

Above a distinct bitumen-water contact, virtually every porous sand in the Athabasca Deposit is saturated with bitumen (Fig. IX-4). The only exceptions are occasional gas legs at the top, or in some rare instances where there is a perched water leg at the top of, or within the bitumen. The areas of thickest pay are controlled primarily by the reservoir thickness and the distribution of facies. In general, the most favourable areas as far as thickness is concerned are along the eastern edge of the deposit towards the main trunk valley system, where thick McMurray Formation sands have accumulated. This area of thick bitumen saturation is limited however, because of the abrupt dip of the reservoir into the water saturated zone over the salt solution collapse edge in the east. Elsewhere the greatest thicknesses occur in sandy facies in the major tributary valleys that trend northeast from the Wainwright Ridge-Grosmont High. One other favourable area is in the southeast over the Primrose - Kirby area where the Wabiskaw Member is relatively thick and continuous, forming deep sand-filled channels that erode into the McMurray Formation (Dekker *et al.*, 1984; Beckie and McIntosh, 1989).

Maximum Continuous Bitumen Pay

One of the fundamental criteria for the evaluation of a favourable bitumen recovery site is the vertical continuity of the pay zone (Fig. IX-5). Shale seals within the succession can interrupt the heating medium (steamflood or gas injection feed for a fireflood), and partition the reservoir, requiring more complicated recovery strategies. Thin shale breaks are probably not effective seals, and therefore argillaceous zones less than 1 metre were not considered as breaks in the vertical continuity in this study. It is not known how thick a shale zone would constitute a reservoir seal, because this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> 50m
40 - 50m
30 - 40m
20 - 30m
10 - 20m
0 - 10m
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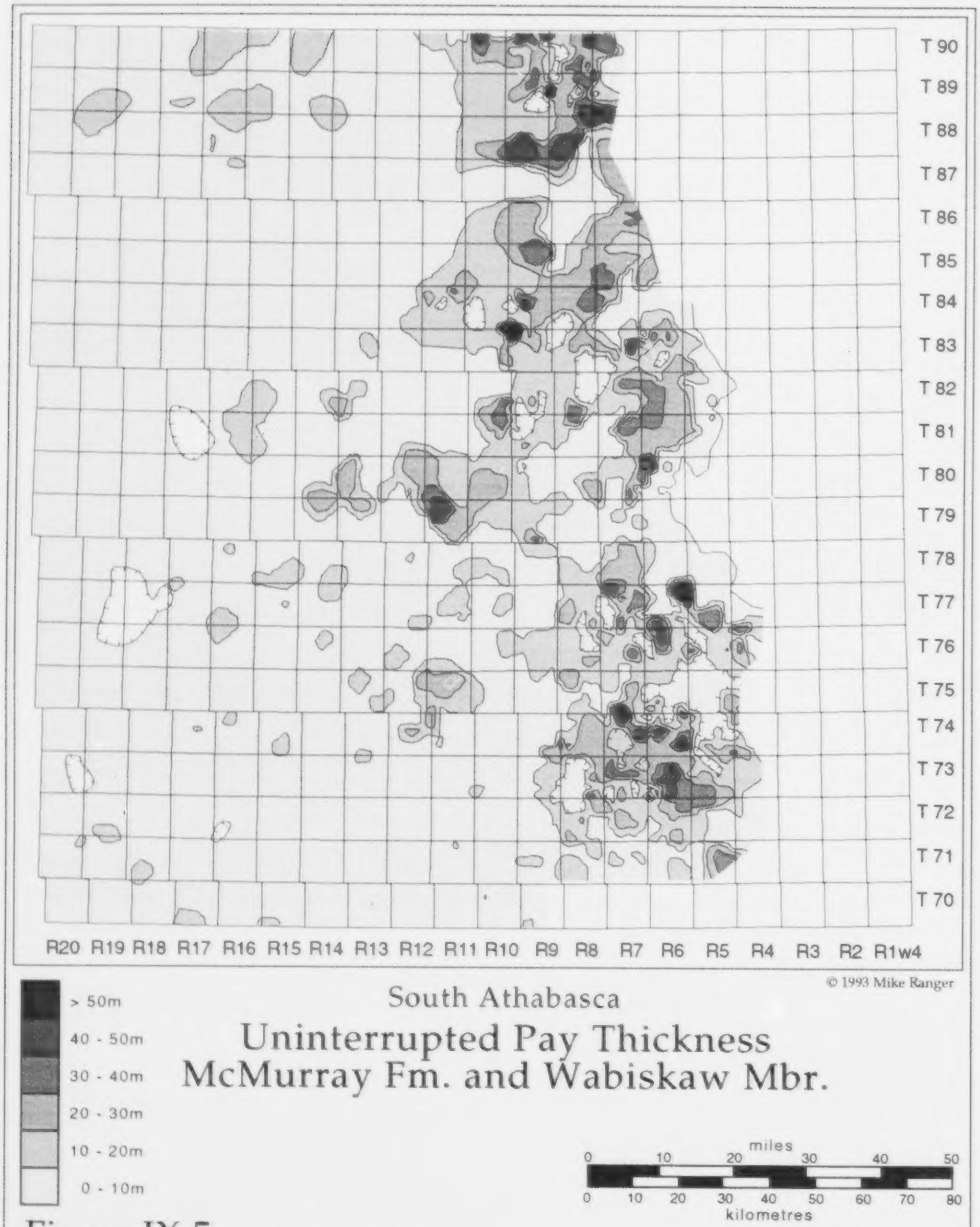
miles
0 10 20 30 40 50
0 10 20 30 40 50 60 70 80
kilometres
Contour Interval: 10m

South Athabasca

Total Bitumen Net Pay
McMurray Fm. and Wabiskaw Mbr.

Figure IX-4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> 50m
40 - 50m
30 - 40m
20 - 30m
10 - 20m
0 - 10m
miles
0 10 20 30 40 50
0 10 20 30 40 50 60 70 80
kilometres

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South Athabasca

Uninterrupted Pay Thickness
McMurray Fm. and Wabiskaw Mbr.

Figure IX-5

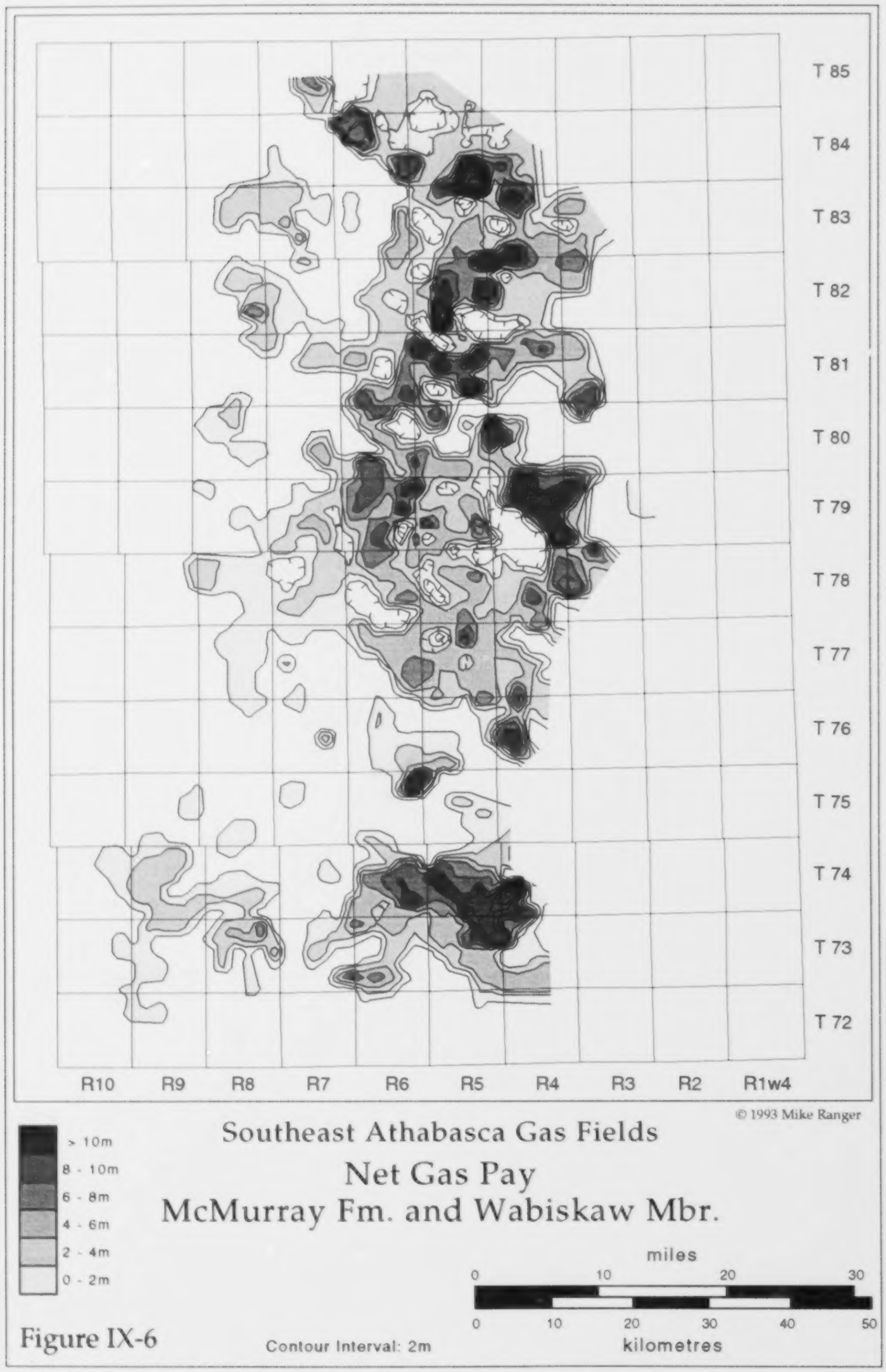
Contour Interval: 10m

probably depends on the recovery technique employed. Flach (1984) uses 3 metres as an arbitrary maximum, but this seems excessive.

Net Gas Pay

In the Athabasca Deposit, bitumen forms only part of the potential energy resource available. Considerable gas is present, especially in the southeastern part of the deposit (Fig. IX-6), which is buried more deeply. As well as being an exploration target for conventional markets, even small sources that may not otherwise be economic may be valuable as a fuel and feedstock for bitumen recovery plants. Their primary potential as cheap local energy sources is obvious, however natural gas is also commonly used as a source of hydrogen for the bitumen upgrading. At present the two existing surface mining plants use natural gas at rate of approximately $100m^3/m^3$ synthetic crude production. The ERCB expects this to increase to approximately $150m^3/m^3$ for future mining and *in situ* plants since the trend is towards more efficient and environmentally acceptable hydrocracking rather than coking as a primary upgrading process (Houlihan and Evans, 1989). Natural gas condensates are also used as bitumen diluents to lower viscosity during pipeline transportation. Nearby sources of gas are therefore a consideration in the decision to build a bitumen recovery plant. On the other hand the presence of a gas leg on top of the bitumen zone can have a detrimental effect on the recovery process. The gas distribution map (Fig. IX-7) shows only gas observed in the McMurray Formation or the Wabiskaw Member, as these may affect the recovery process. Large reserves also exist in the overlying Grand Rapids and Clearwater Formations (*e.g*,. Hangingstone, Leismer, Kirby fields) and, towards the west in the underlying Devonian carbonates (*e.g.*, House, Granor, Saleski fields).

The presence of gas is common over much of the south Athabasca Deposit, although many of the accumulations are less than 5 m in thickness. Every occurrence, whether obvious from well logs or only suspected, is shown on the map, as the presence of even minor amounts in a well may be the edge of a larger accumulation, and could form the basis for further exploration (or could interfere with the recovery process). Some wells produce gas on drill stem tests from a zone that is not obviously gas-bearing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R2
R1w4
> 10m
8 - 10m
6 - 8m
4 - 6m
2 - 4m
0 - 2m
miles
0
10
20
30
0
10
20
30
40
50
kilometres

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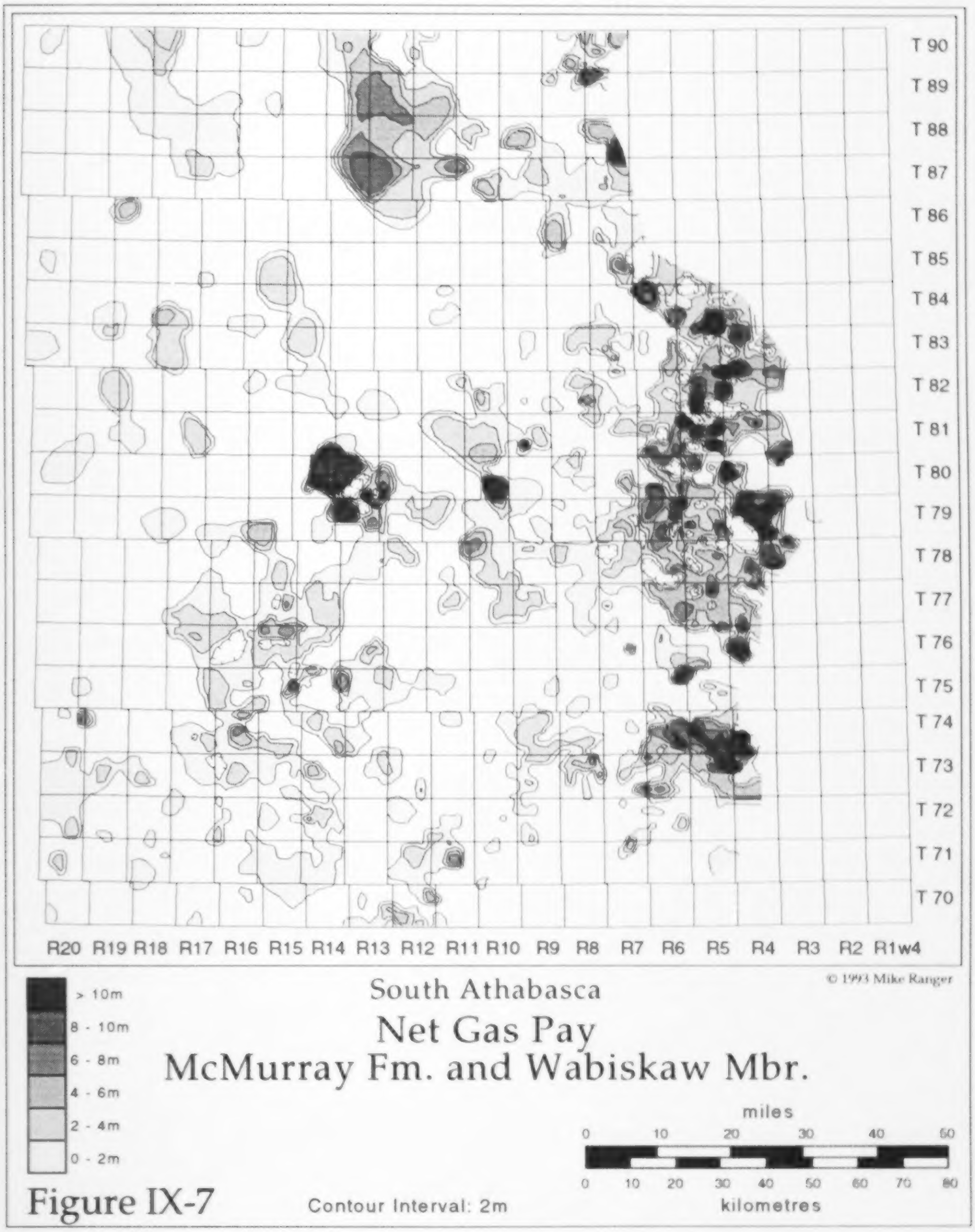
Southeast Athabasca Gas Fields

Net Gas Pay

McMurray Fm. and Wabiskaw Mbr.

Figure IX-6

Contour Interval: 2m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> 10m
8 - 10m
6 - 8m
4 - 6m
2 - 4m
0 - 2m
miles
0 10 20 30 40 50
0 10 20 30 40 50 60 70 80
kilometres

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South Athabasca

Net Gas Pay

McMurray Fm. and Wabiskaw Mbr.

Figure IX-7

Contour Interval: 2m

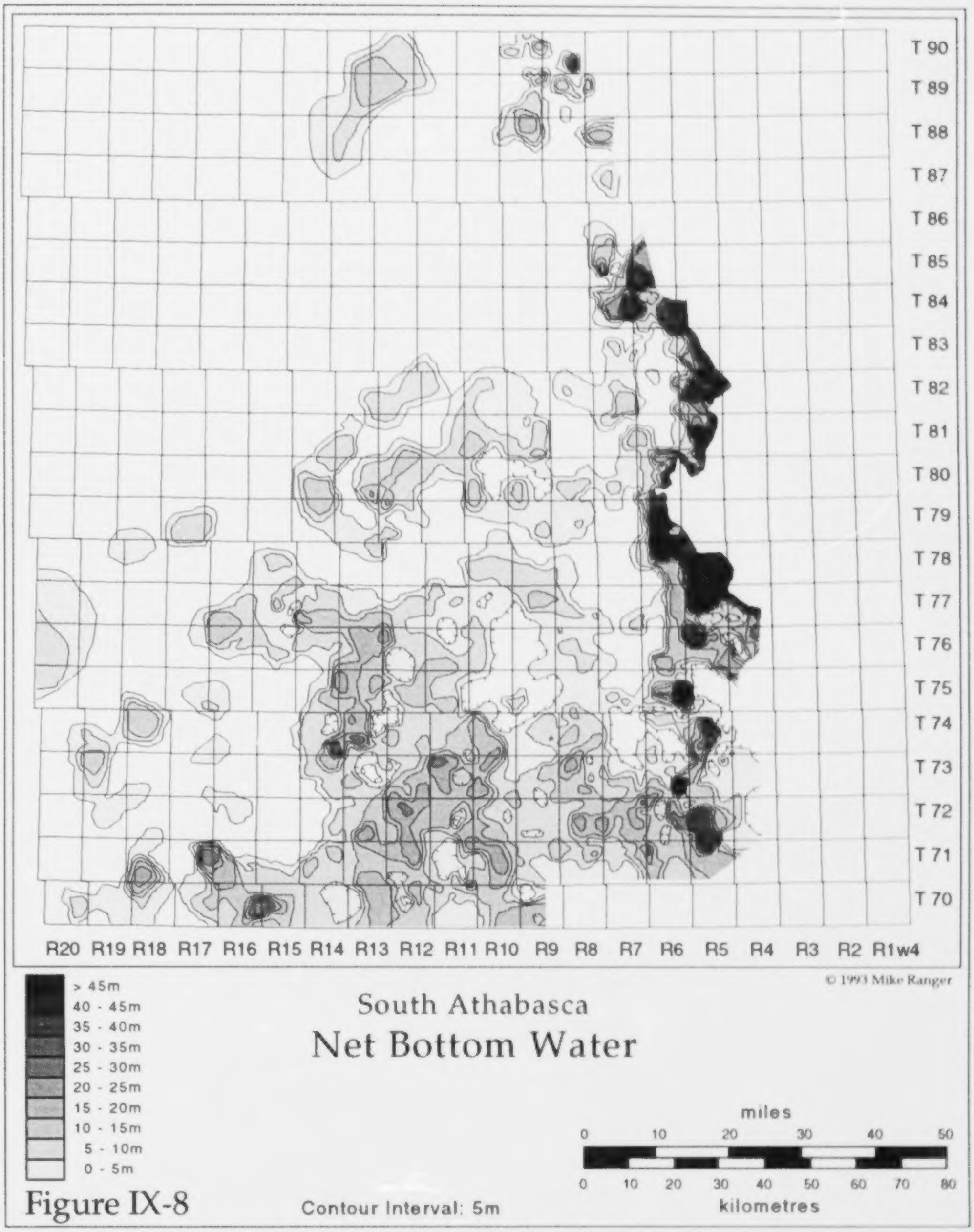
on geophysical logs. These wells probably produce gas that is in solution at reservoir conditions.

Most of the major gas accumulations occur along the eastern edge of the deposit, commonly somewhat beyond the bitumen-water contact. Gas from the McMurray-Wabiskaw interval is produced from several fields in this area: Kirby, Graham, Newby and Hardy. There are many other gas-bearing wells along this trend, some of which contain up to 25 m of pay. The other significant area of gas accumulation is the Thornbury field in township 80, range 13 and 14W4 where up to 20 m of pay has been penetrated.

Much of the gas is demonstrably trapped in structural highs, but in other areas the lack of an obvious structural component to the trap suggests that stratigraphic trapping plays some role. Given the facies complexity of the McMurray Formation, it would be expected that many gas accumulations would have some component of stratigraphic trapping. However, no area has been found with sufficient well control to demonstrate this. Because the gas overlies the bitumen, and shares the same reservoirs, it can be surmised that most of the gas migrated at approximately the same time as the oil, but no later than the time of degradation of the oil to bitumen, since once degraded the bitumen is immobile and could not have been displaced. Later migration of gas into the reservoir could probably have accumulated only in solution with the bitumen, and not as a discrete phase. The bitumen-water contact originally being flat, later-generated gas would have bypassed the saturated area of the reservoir, and continued updip. This is a possible explanation for the presence of thick gas accumulations on the eastern edge of the Athabasca Deposit, beyond the bitumen saturated zone.

Water

A distinct and mappable basal oil-water contact exists below the south Athabasca Deposit, and it appears to be a continuous horizon (Fig. IX-8). The bitumen-water contact is not horizontal with respect to present day sea level, as one would observe in most conventional oil fields. Because the bitumen is immobile, the bitumen-water contact is stratigraphically "frozen" in place, and dips gently to the southwest in the same direction as the reservoir rocks, but at a slightly lesser angle (Fig. IX-9). In addition, in the easternmost part of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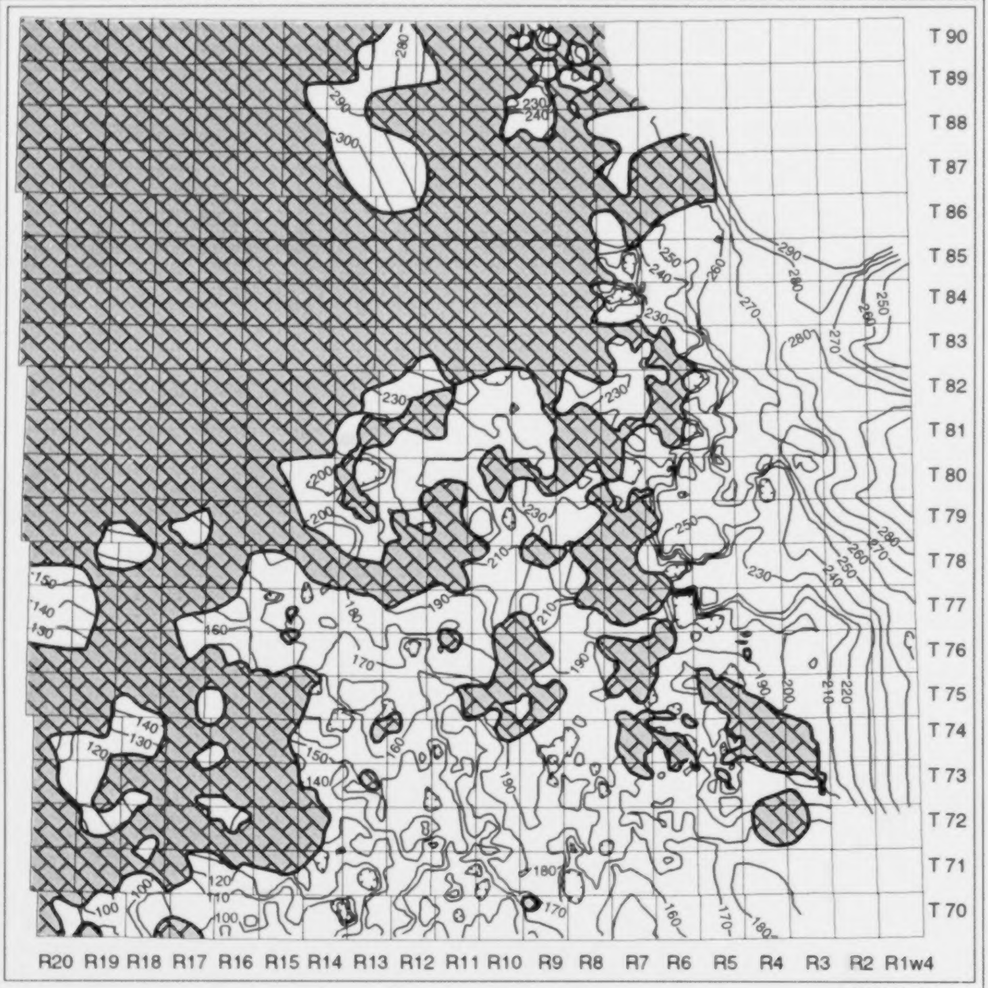
R20 R19 R18 R17 R16 R15 R14 R13 R12 R11 R10 R9 R8 R7 R6 R5 R4 R3 R2 R1w4
© 1993 Mike Ranger
> 45m
40 - 45m
35 - 40m
30 - 35m
25 - 30m
20 - 25m
15 - 20m
10 - 15m
5 - 10m
0 - 5m
South Athabasca
Net Bottom Water
miles
0 10 20 30 40 50
0 10 20 30 40 50 60 70 80
kilometres
Contour Interval: 5m

Figure IX-8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R3
R2
R1w4
280
290
300
230
240
250
260
270
290
280
270
260
250
230
200
210
190
180
170
160
150
140
130
120
110
100

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South Athabasca

Structural Elevation of the Bitumen - Water Contact

Datum: sea level
Contour Interval: 10m

▨ Bottom water not present

miles
0
10
20
30
40
50
0
10
20
30
40
50
60
70
80
kilometres

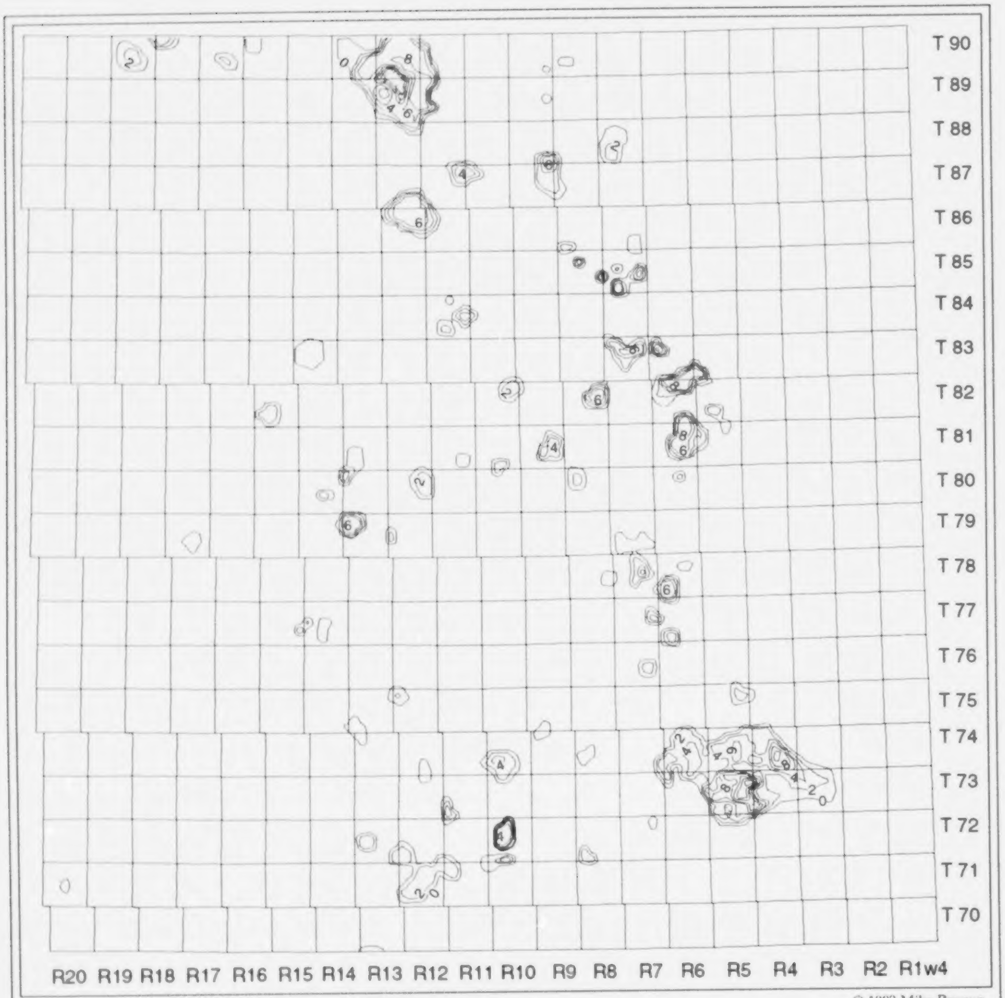
Figure IX-9

the study area, the bitumen saturation ends abruptly, approximately coincident with the thickest accumulation of the sand in the McMurray Formation, producing thick accumulations of barren reservoir.

Besides obviously limiting the extent of the reservoirs, the existence of a basal water phase can have a strong effect on any heat injection, *in situ* bitumen recovery process. A thick water zone can be detrimental, acting as a heat sink (also known as a heat thief zone), and frustrating attempts to heat the bitumen phase of the reservoir. On the other hand, some recovery processes may benefit from the existence of a thin to moderate thickness of water phase below the bitumen, helping to more uniformly distribute the heating media through the reservoir from below, a process that may otherwise be hindered by the low relative permeability of the bitumen plugged reservoir sands.

The basal water leg exists under much of the south central and eastern area of the south Athabasca Deposit, reaching a gross maximum thickness of approximately 30 m in the south. To the north and west the Paleozoic unconformity is structurally high, and the bitumen-water contact abuts against it, eliminating the water leg. There are two major areas with anomalously thick basal water zones. The first, in the southeast within townships 72 to 75 and ranges 5 to 6W4, is up to 90 metres thick. It is coincident with an anomalous structural low on the unconformity surface, which is filled with McMurray Formation sediments. This structural low could be a relatively deep major erosional valley on the unconformity (in which case it cannot be considered anomalous), or alternatively could be the result of salt solution collapse before or during deposition of the Lower Mannville. The second anomalous area is in the northeast within townships 84 and 85, ranges 6 and 7W4, and is up to 50 metres in thickness.

Intra-formational water refers to water zones that occur within the Wabiskaw- McMurray reservoir, but above the basal oil/water contact (Fig. IX-10). There are two apparent reasons for the occurrence of intra-formational water zones. First, two or more porous sand intervals may be stratigraphic traps separated vertically from each other by shales that seal them into separate reservoirs. Then each one of these reservoirs can have separate oil, gas and water phases during migration and trapping.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R20 R19 R18 R17 R16 R15 R14 R13 R12 R11 R10 R9 R8 R7 R6 R5 R4 R3 R2 R1w4

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South Athabasca

Net Water Sand
overlying or within the
Bitumen Zone

Figure IX-10

Contour Interval: 2m

miles
0 10 20 30 40 50
0 10 20 30 40 50 60 70 80
kilometres

Second, because the bitumen forms essentially an immobile fluid phase, the normal fluid density relationships in the reservoir may display anomalous relationships. These take the form of water zones lying on top of the bitumen zones, with no intervening seals, save the bitumen itself. These "perched" water zones are evidence for the original existence of a gas phase in the reservoir. After immobilisation of the bitumen due to degradation, the gas has either diffused with time through the overlying seal or the seal may have been breached by minor faults. The escaping gas is then displaced by formation water, because the bitumen phase cannot respond by changing its base level. Indeed it is not uncommon to observe a remnant of the gas phase at the top of the reservoir. Either total diffusion of the gas through the reservoir seal has not had time to occur, or, if the trap was breached by a fault, the breach is below the apex of the trap leaving a small pool of gas at the top, underlain by a water leg which is in turn underlain by the original but degraded and immobilised bitumen phase.

In some cases a combination of multiple reservoirs and perched water zones cause a stacked succession of gas - water - bitumen or water - bitumen phases. These paleo-gas water legs can have important effects on any in-situ recovery process. A water phase overlying the bitumen can be particularly detrimental, acting as a heat thief zone. On the other hand, a water phase between two bitumen zones such as might occur within stacked reservoirs may be beneficial, helping to distribute the injected heat more uniformly through the reservoir.

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CHAPTER X

GENERAL DISCUSSION, SUMMARY, AND CONCLUSIONS

This study of the Athabasca Oil Sands Deposit has yielded two major conclusions. First, a framework for a new, detailed, stratigraphic scheme is proposed for the McMurray Formation, tying in the facies associations to basin-wide correlations based on sea-level fluctuations. Second, new evidence has been presented to show that migration, trapping and degradation of the bitumen occurred no later than the Late Cretaceous. In addition this new data allow a reconstruction of the trapping mechanism at the time of migration.

STRATIGRAPHY AND SEDIMENTOLOGY

Correlatable, coarsening-upward, genetic units are recognised in the upper part of the McMurray Formation. They are recognised both in gamma ray log correlations, and in a statistical analysis of the facies and facies successions. These genetic units have all the characteristics of a shoreface, although with a distinct brackish overprint expressed by the ichnofossil assemblages. In a sequence stratigraphic scheme, the shoreface sediments are parasequences representing highstand systems tracts, and are separated by marine flooding surfaces. They have a distinct gamma-ray log signature, and can be recognised over much of the south Athabasca area. The distribution of these shoreface parasequences is irregular, but not without pattern. Lowstand systems tracts are also common and in fact dominate the stratigraphic column in most areas. The lowstand deposits constitute complex fills in channels that have eroded the shoreface parasequence sets. The channels are predominantly filled with estuarine deposits, mainly muddy to sandy estuarine point bars, although the lower parts of the deeper channels are commonly freshwater fluvial in nature. Only the upper part of the McMurray Formation has been correlated in detail using this new stratigraphic scheme, but there is ample evidence from gamma-ray logs that the shoreface parasequences are also present throughout the McMurray. However their preservation potential appears to decrease with depth.

There is no doubt that much of the McMurray Formation in the Athabasca Deposit was deposited under marginal marine conditions. This is expressed in the studies of the ichnofauna, without which such a conclusion would be difficult to arrive at based on physical sedimentology alone. Both lowstand and highstand systems tracts are overprinted with ichnofossil suites that contain brackish indicators. These characteristics are typical of a stressed environment, and include: 1) low diversity of ichnotaxa but typically a high abundance of individual forms; 2) presence of an impoverished marine assemblage of ichnofauna rather than a mixed freshwater/marine assemblage; 3) presence of elements of both the *Cruziana* and *Skolithos* ichnofacies; 4) a bias towards morphologically simple structures reflecting simple feeding strategies; and 5) a tendency towards diminished size (Dörjes and Howard, 1975; Wightman *et al.*, 1987; Beynon *et al.*, 1988; Pemberton and Wightman, 1992).

Nowhere in the McMurray Formation is there indication of a fully marine assemblage. There are also no non-marine ichnofossil assemblages, however barren zones are common, and these are associated with freshwater fluvial or paludal environments.

Detailed paleogeographic mapping suggests that the dominantly brackish nature of the basin is probably a result of a narrowing at its mouth formed by the convergence of the Grosmont High with the highlands of the Canadian Shield, which hindered dissipation of fresh water into the boreal sea.

Sedimentology of the Wabiskaw Member

The Wabiskaw Member is a minor reservoir of the Athabasca Deposit. Yet the presence of relatively high gravity bitumen, recoverable on primary production in the Wabasca area, makes it an important exploration target. Detailed study of the stratigraphy of the Wabiskaw Member has shown that it can be subdivided into three mappable overlapping sand units.

For many years these sand bodies were thought to represent offshore bars, as they filled all the criteria of the depositional model proposed for other such sand bodies in the western interior basin (Ranger, 1982). Each of the Wabiskaw sands is herein reinterpreted as a lowstand shoreface preserved on a shallow shelf. They can be shown to onlap the shoreline of a Paleozoic highland, which remained exposed to the northwest during early Clearwater transgressions. Each of the three sands has similar facies successions, and they coarsen and become sandier upwards. These characteristics, as well as the trace fossil assemblages (Ranger *et al.*, 1988), all support the interpretation as shoreface sand bodies. Facies denoting beach/foreshore environments or any indication of exposure are lacking, suggesting that each transgressive phase may have been accompanied by erosion, or that, especially basinward to the northeast, only lower to middle shoreface environments ever existed, and flooding is represented only by a change to deeper water facies.

MIGRATION AND TRAPPING

One of the consequences of acquiring an extensive database of well information for this study, has been that it has allowed a detailed regional look at the physical nature of the reservoir. The bitumen distribution maps and the structure maps using present day sea level as a datum shed no new light on the problem of the trapping mechanism years, for which there had been different theories proposed going back over 60 years.

However, the bitumen can be shown to be immobile in the reservoir, and where the bitumen/water contact is mapped, it is seen to dip to the southwest, parallel to Laramide foreland basin subsidence, but at a somewhat lesser angle than the reservoir host strata. This indicates that it was in place and immobilised very early in the onset of the Laramide orogen. Therefore early oil generation, migration and trapping must have taken place, probably no later than Late Cretaceous.

This observation has several implications. Since oil generation did not begin until the source rocks were buried to sufficient depths, also early at the onset of the Laramide orogen (Deroo *et al.*, 1977), generation and migration of vast quantities of hydrocarbon must have occurred relatively rapidly. Furthermore, the large hydraulic head due to uplift of the Rocky mountains (mostly Tertiary) invoked in some studies as the mechanism for triggering migration as massive fluid flow to the northeast (Garven, 1989), would have been only at an incipient stage in Late Cretaceous time. The bitumen was already in place and degraded by the time such a hydraulic system could have been at maximum strength. This suggests that the migration mechanism must have been dominantly gravity/density and buoyancy.

By flattening the reservoir using the bitumen-water contact as a datum, the original configuration of the trap can be reconstructed. Where this is done, the trap is revealed to be a simple, shallow, anticlinal structure but of tremendous areal size. A major stratigraphic component to the trap is proposed for the northeast. There the trap probably consisted of a leaky seal of overlying Clearwater shales onlapping the Precambrian regolith.

EFFECTIVENESS OF DIGITAL METHODS

Data Collection and Display

The methods and conclusions that result from this study have relied heavily on the computerised collection of large volumes of data, and the computerised analyses and graphic display of these data. Such an undertaking would not have been practical even ten years ago without the rapid advance in computer, especially microcomputer, technology. Advances in the sedimentologic and stratigraphic understanding of the lower Mannville Group in the Athabasca area appeared to have reached a plateau in recent years, beyond which localised studies could not easily advance. The value, and indeed the necessity, of using large volumes of regional data in complex stratigraphic terranes is one of the major contributions made by this study. Furthermore, with these large amounts of data, innovative techniques for display are required. The custom-written software for the display and correlation of the digitised geophysical logs was a main component of this study. It is possible to produce cross-sections in any direction displaying over one hundred wells simultaneously, in a matter of seconds. Even a single cross-section of this length would be a formidable task if attempted by hand.

Another consequence of acquiring large volumes of data, is the ability to produce paleogeographic maps in greater detail than was previously possible. Yet this greater detail presents problems of its own; hand contouring is out of the question, and the intricate maps produced by computer contouring are difficult to comprehend when displayed in traditional black contour lines.

The ability to produce full colour and gray shaded contour fills on a microcomputer has evolved quickly, and is used to advantage in this study. At the outset of this study, such procedures were available only with considerable effort and expense on mainframe computers.

Statistical Approaches to Facies Analysis

The statistical methods used in this study, especially Markov analysis, have not been utilised in many published studies. There are several reasons for this. First, it is a technique not easily carried out by hand, especially if the recommended tests of significance are to be calculated. Second, there are no "off-the-shelf" programs available commercially to do the calculations, although the code for the technique has been published (Wells, 1989). Finally there has generally been a feeling that the analysis essentially "tells you what you already know" from subjective observation. This latter point must be addressed here.

It is true that for very simple facies successions, Markov analysis may have little practical value. Furthermore, for small studies, not enough data may be collected to produce results that have statistical significance. The more complex and numerous the facies, the more samples will be required to produce significant results. On the other hand some results of Markov analysis that are not usually recognised as being useful, can enhance even a simple interpretation. For instance, most researchers think that the only use is to bring out the significant "preferred" facies transitions, *i.e.*, the vertical facies associations. However, just as important may be those transitions that are extremely unlikely to occur, or that appear to be random. If, for instance, it is extremely rare to observe a facies interpreted as middle shoreface pass into an erosion surface, rapid basin subsidence may be indicated. As an another example, if a particular facies does not have any preferred transition into it *i.e.*, the transition is "random", its base may be a significant sequence stratigraphic boundary, such as a flooding surface or even a sequence boundary where no erosion is obvious. This observation is particularly true for data collected from repeated samples through the same interval, such as is common in a core study. The point to be made is that a simple facies succession may be easily recognised, and a rigorous and carefully interpreted

Markov analysis may "tell you what you already know" about the transition pattern that is present. Yet there may be additional useful information to be gleaned from the improbable and random transitions that are not obvious because they represent the absence of a facies association.

In a complex facies succession such as is present in the McMurray subbasin, the benefits of the Markov analysis are clear. Markov analysis is able to differentiate a simple shoreface succession from a complex channel fill succession. Each of these can be interpreted as follows: highstand systems tract (prograding shoreface), lowstand systems tract (channels), transgressive systems tracts (channel fills). The paleosols and rooted horizons stand out as a discrete zone or a horizon, not exclusively related to either the shoreface or the channel fills. Before the Markov analysis was run, these facies relationships were not obvious, being masked by the relatively large number of complex facies and by the complex, brackish, ichnofaunal overprint.

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